Free-Space and Indoor Wireless Optical Communication Systems

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Outline

- Research Group
- Introduction
  - Definitions and Applications for OW and FSO Links
- Indoor Optical Wireless Communications
  - Optical intensity channel, amplitude constraints
  - DSD
  - Binary-Level MIMO System
  - Prototype
- FSO Links
  - FSO Channel model, challenges
  - Outage Capacity Design Methodology
  - Experimental Links
- Conclusions & Future Directions

Research Group

- Free-Space Optical Communication Algorithms Laboratory

FOCAL

Free-Space Optical Communication Algorithms Laboratory

1. Modem design for FSO and indoor optical wireless
   - Theory and simulation studies
2. Prototype Demonstrations

What is Optical Wireless?

- Unguided or Wireless communications using optical band emissions (both coherent or incoherent)

- Terminology:
  - Optical Wireless (OW)
  - Free-Space Optics (FSO)

Early Optical Wireless Links

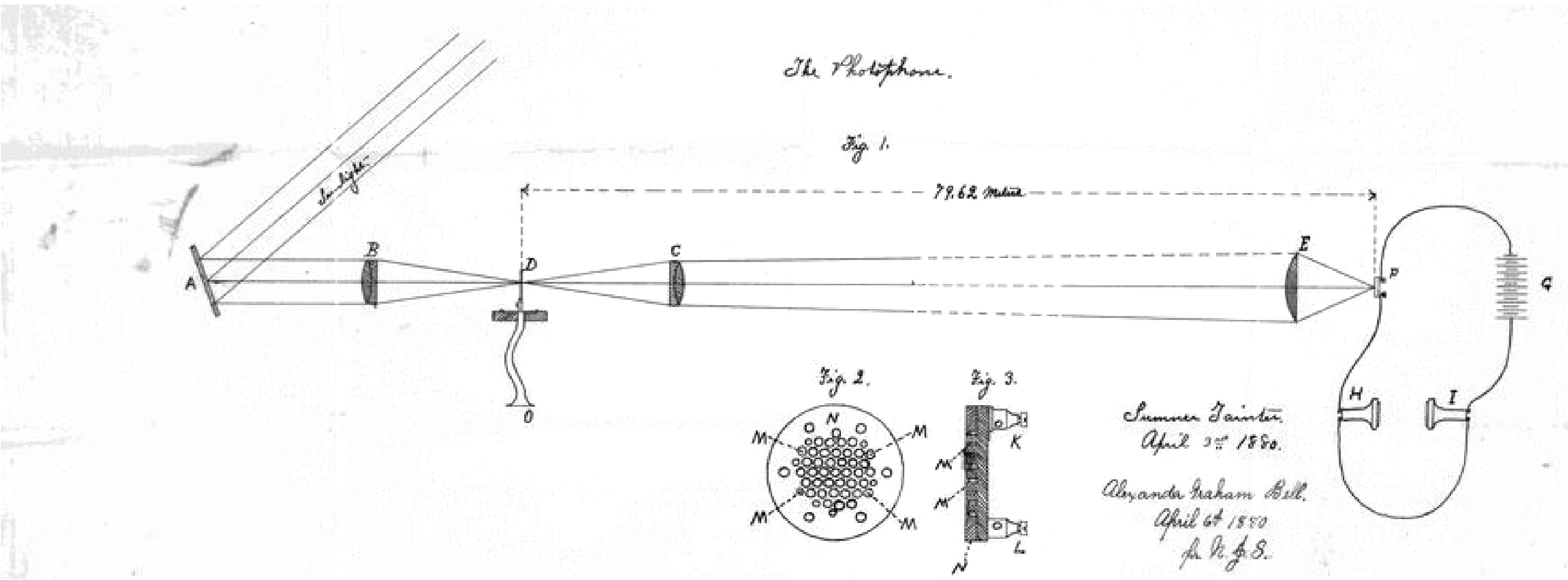
- The ancients (< 1200BC ?)
  - Fire Beacons

Early Optical Wireless Links

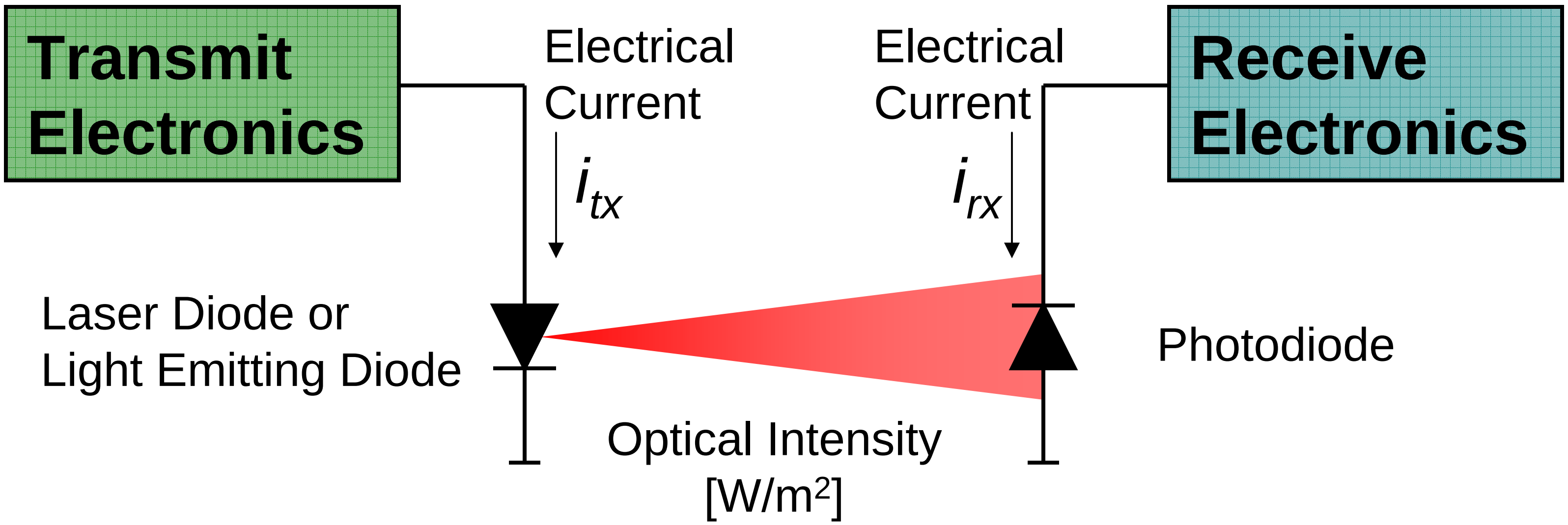
- Claude Chappe (1790's)
  - Optical Telegraph

Early Optical Wireless Links

- A.G. Bell & C.S. Tainter (1880)
  - Photophone

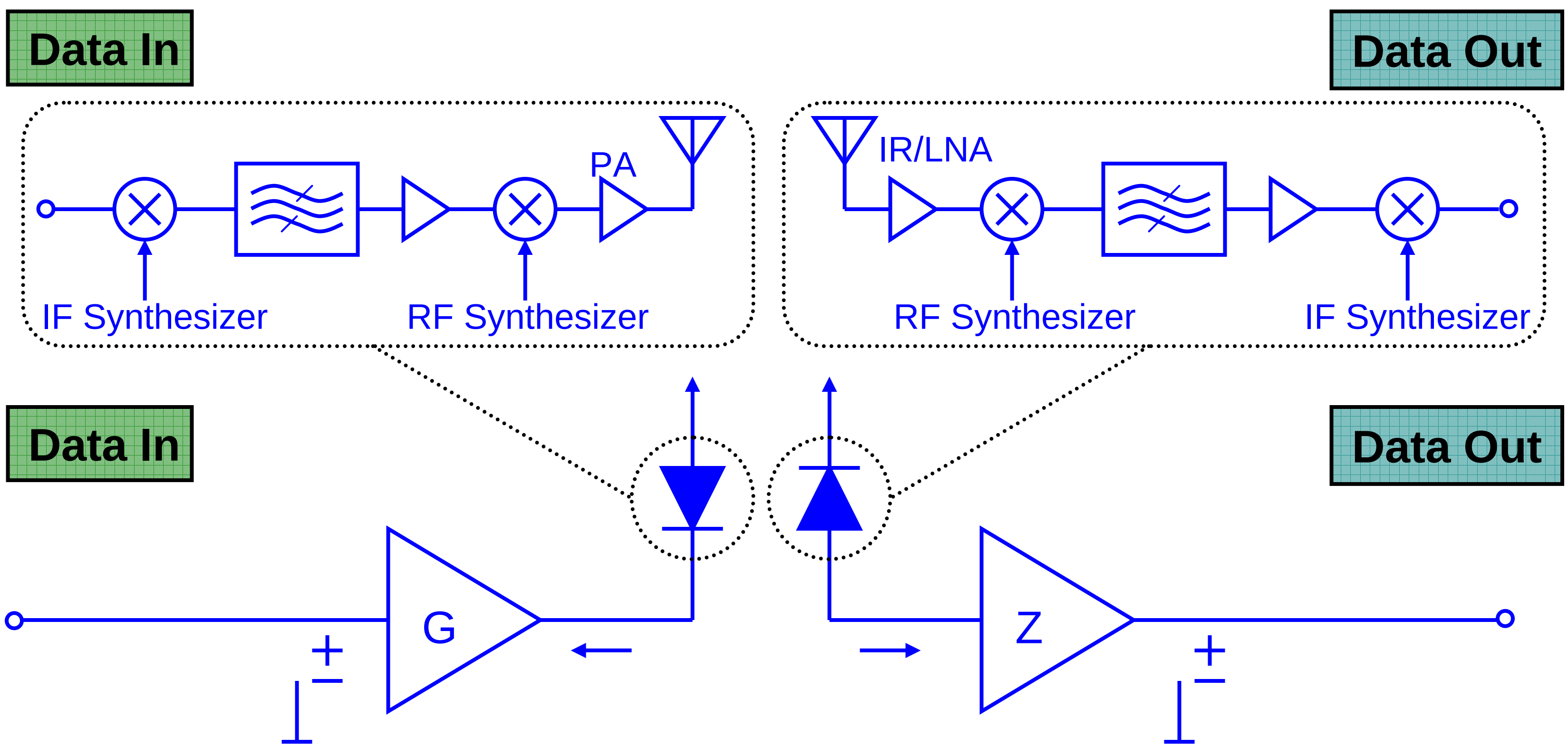


Optical Wireless Channels



- Optical Intensity Modulated
- Direct Detection
- Amplitude constraints
  - Non-negativity
  - Eye-Safety Requirement

Comparison of OW versus RF

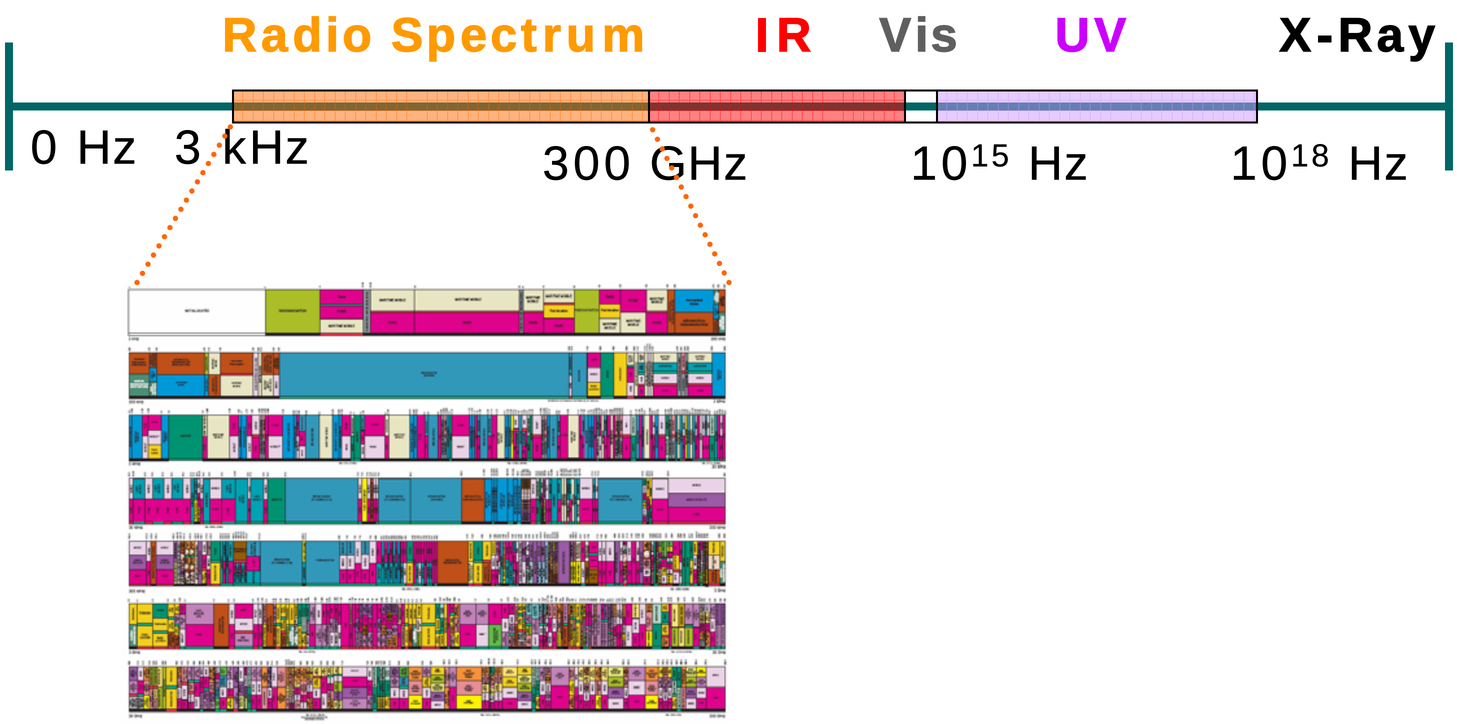


- All electrical signals at baseband!

Advantages/Disadvantages of OW

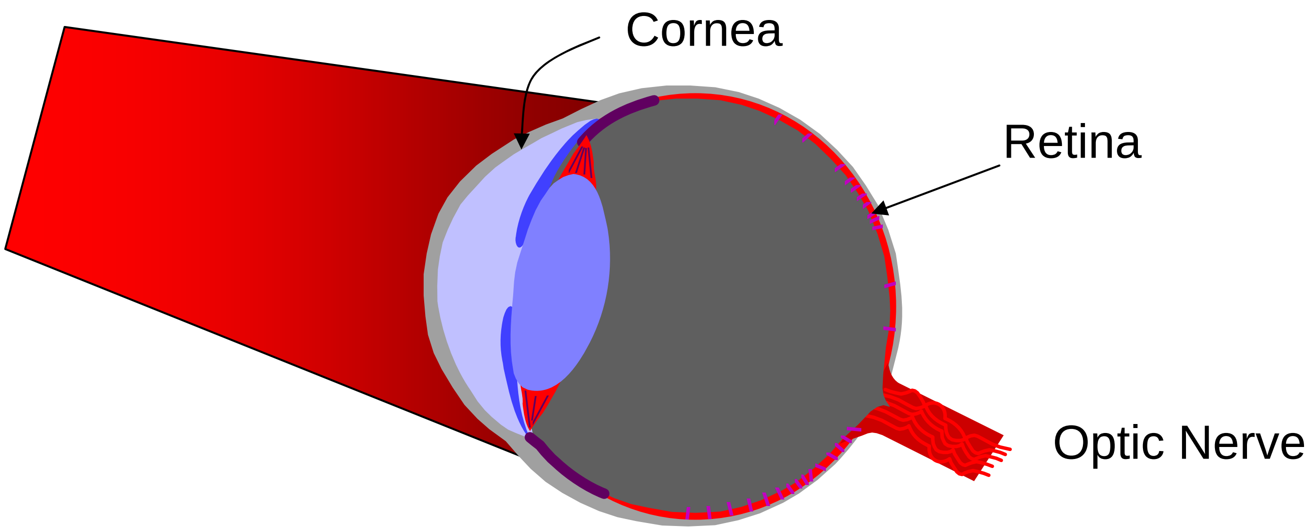
- **Advantages**
  - Low cost, base-band circuit design
  - Unregulated bandwidth
  - High date rates (Gbps)
  - Inherently high-security, less *multiaccess* interference
- **Disadvantages**
  - Cannot pass through walls
  - Sensitive to blocking
  - Limited Transmit Power

Available Spectrum



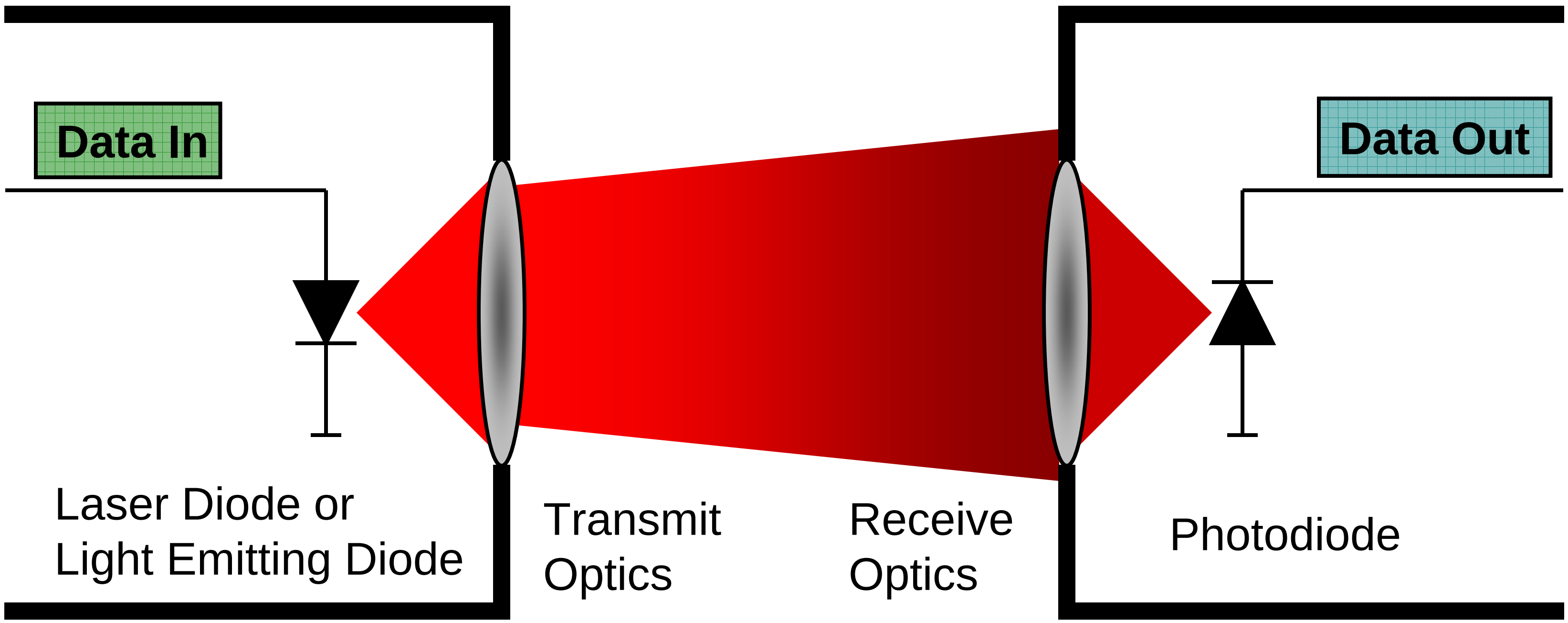
- Huge amount of unregulated bandwidth = potentially high rates
- **Immune** to RF interference
- Radiation is confined – inherent security

Eye-Safety Requirement



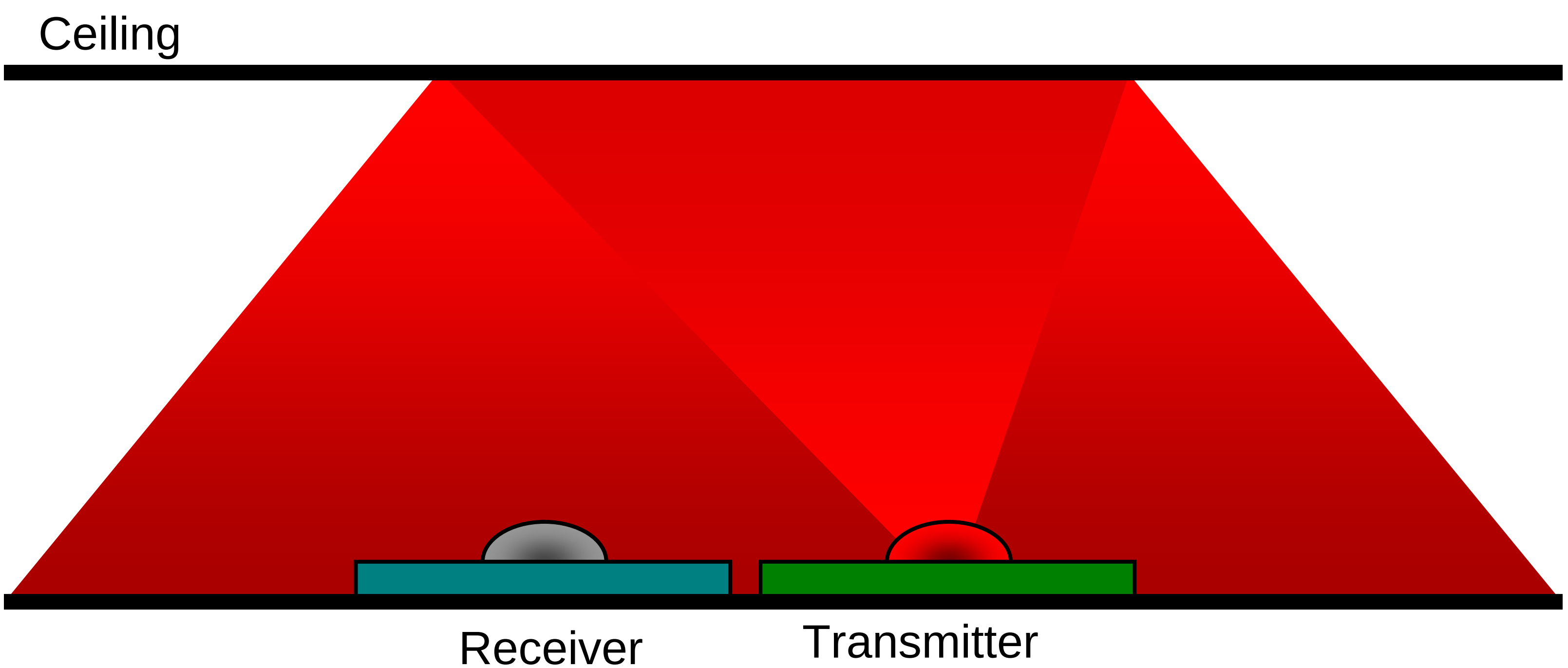
- At near IR (λ = 700-1000 nm), human eye focuses radiation much like visible wavelengths
- Cornea nearly opaque for λ > 1400 nm
- Average transmitted optical power is limited

Directed Links



- IrDA standard (FIr) 4Mbps over 1 m (4-PPM)
- FSO links 2-4 Gbps over 2-5km.
- Require pointing, long range, high speed

Non-Directed Links

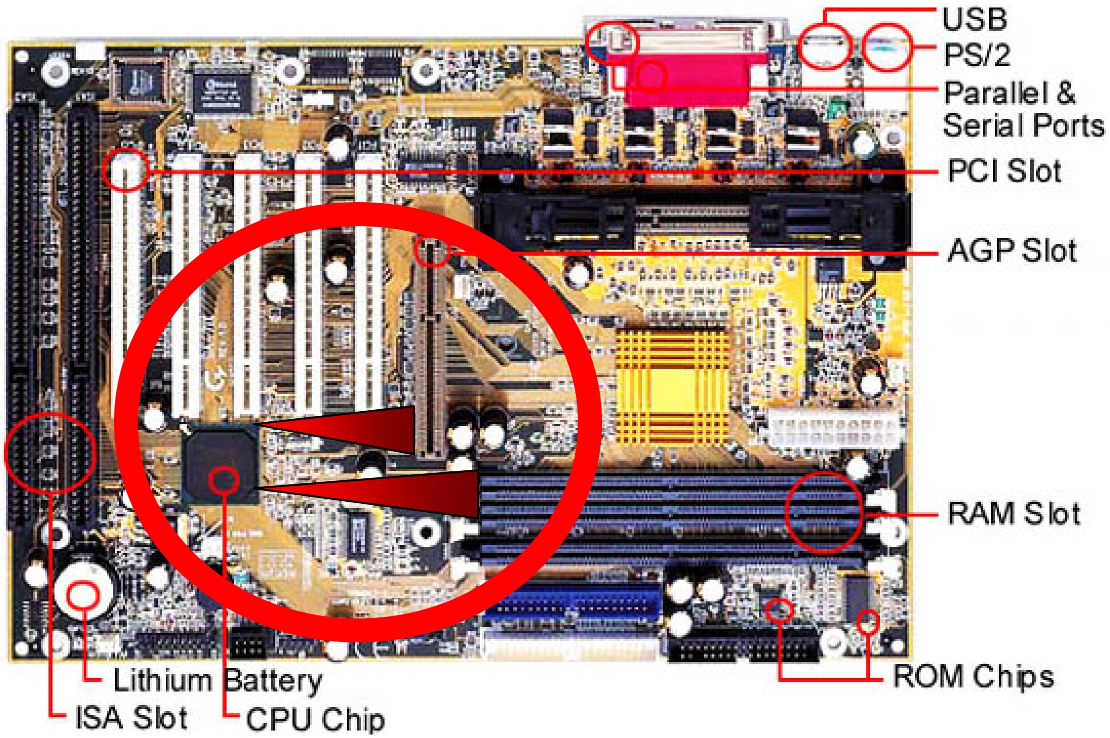


- IrDA standard (AIr) 4Mbps (typ. in a 5m radius)
  - 4-PPM with repetition coding
- Multipath distortion

Applications

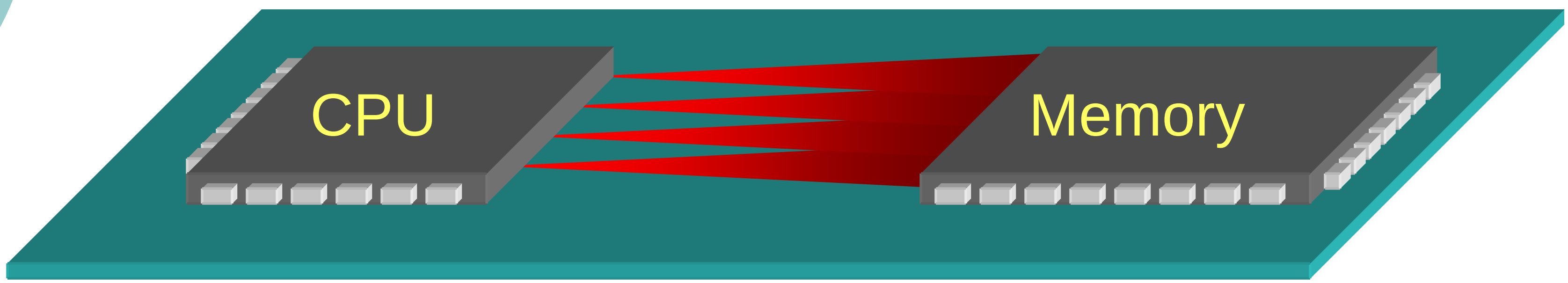
- Short range (cm – m)
- Medium range (m – 10 m)
- Long range (km)

Chip-to-Chip Signalling



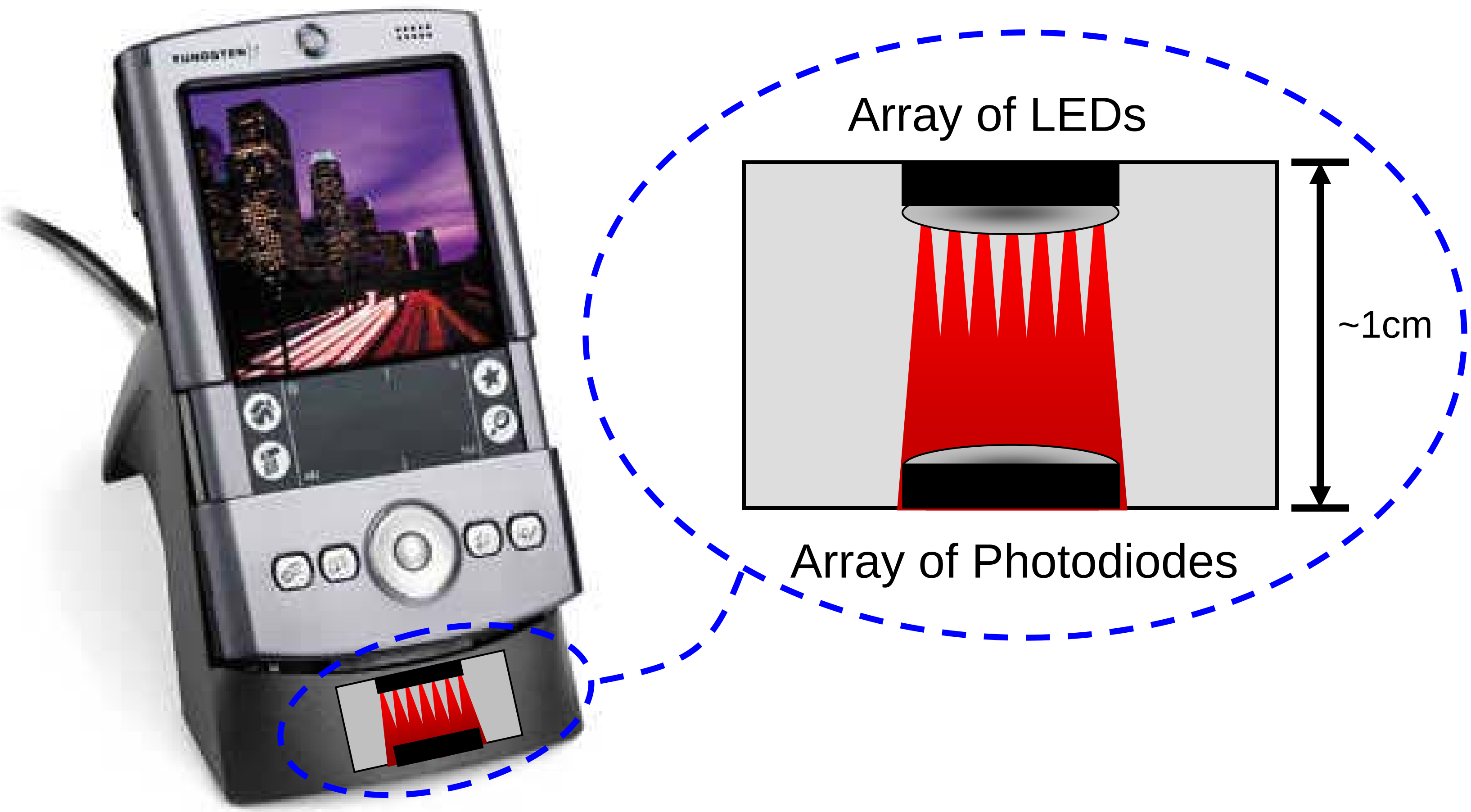
- High speed link to main memory and video

Multi-Element Chip-to-Chip Interface

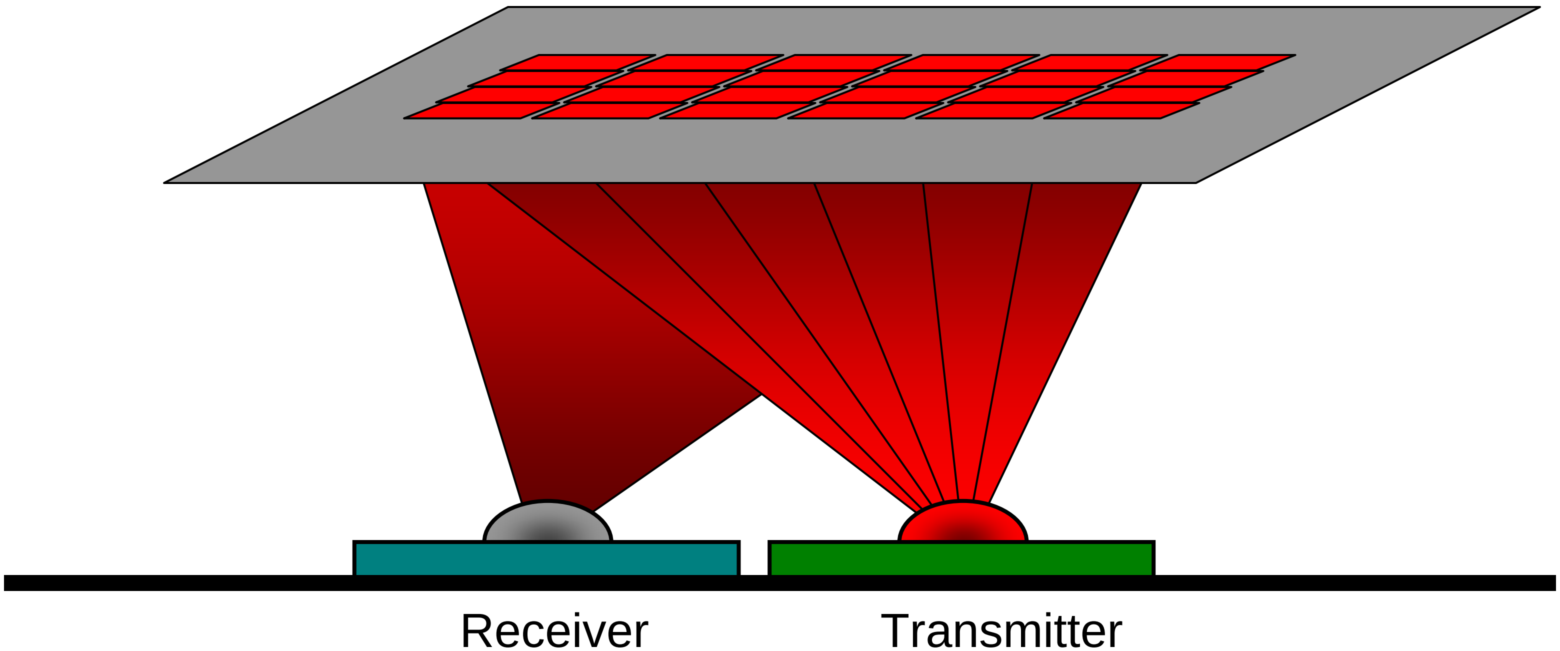


- Multi-pixel
- High Rate
- High interconnect density
- Low Power
- Power supply independent
- No EMI

Device Interconnect

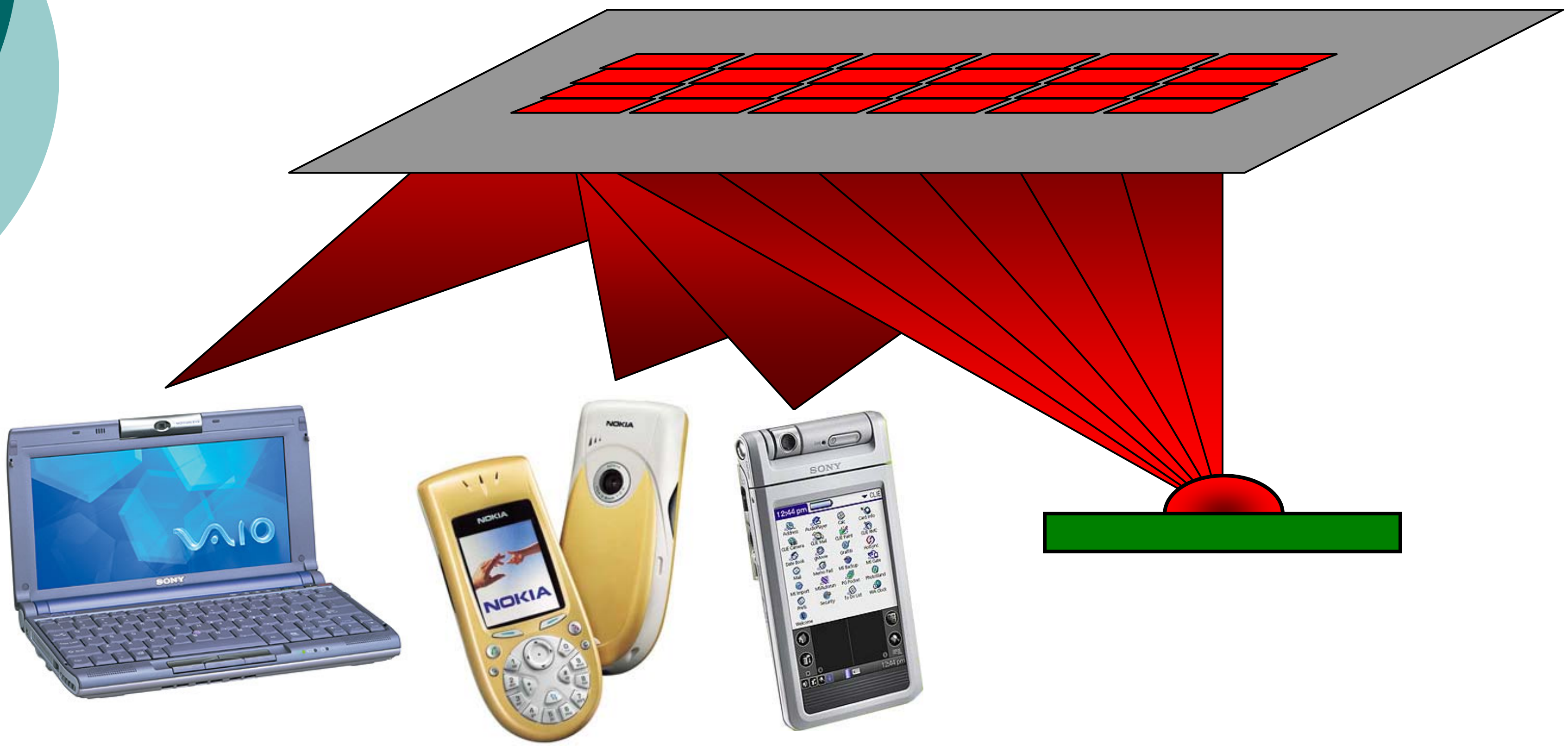


Wireless Optical LAN



- Transmitter constructs a series of images which are transmitted to receiver

Wireless Optical LAN

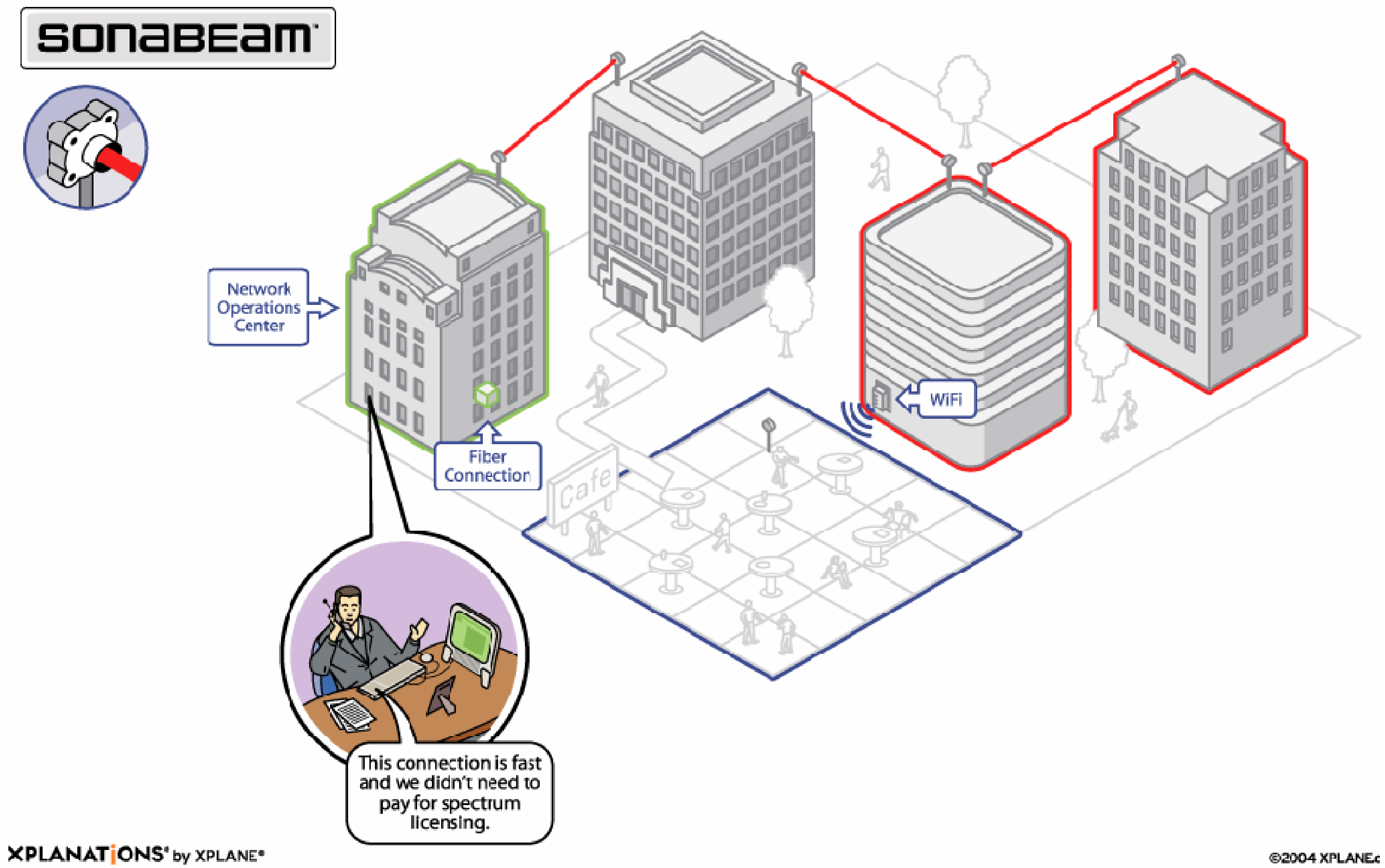


- Receivers can leverage the existing imaging abilities of devices

Optical Wireless LAN

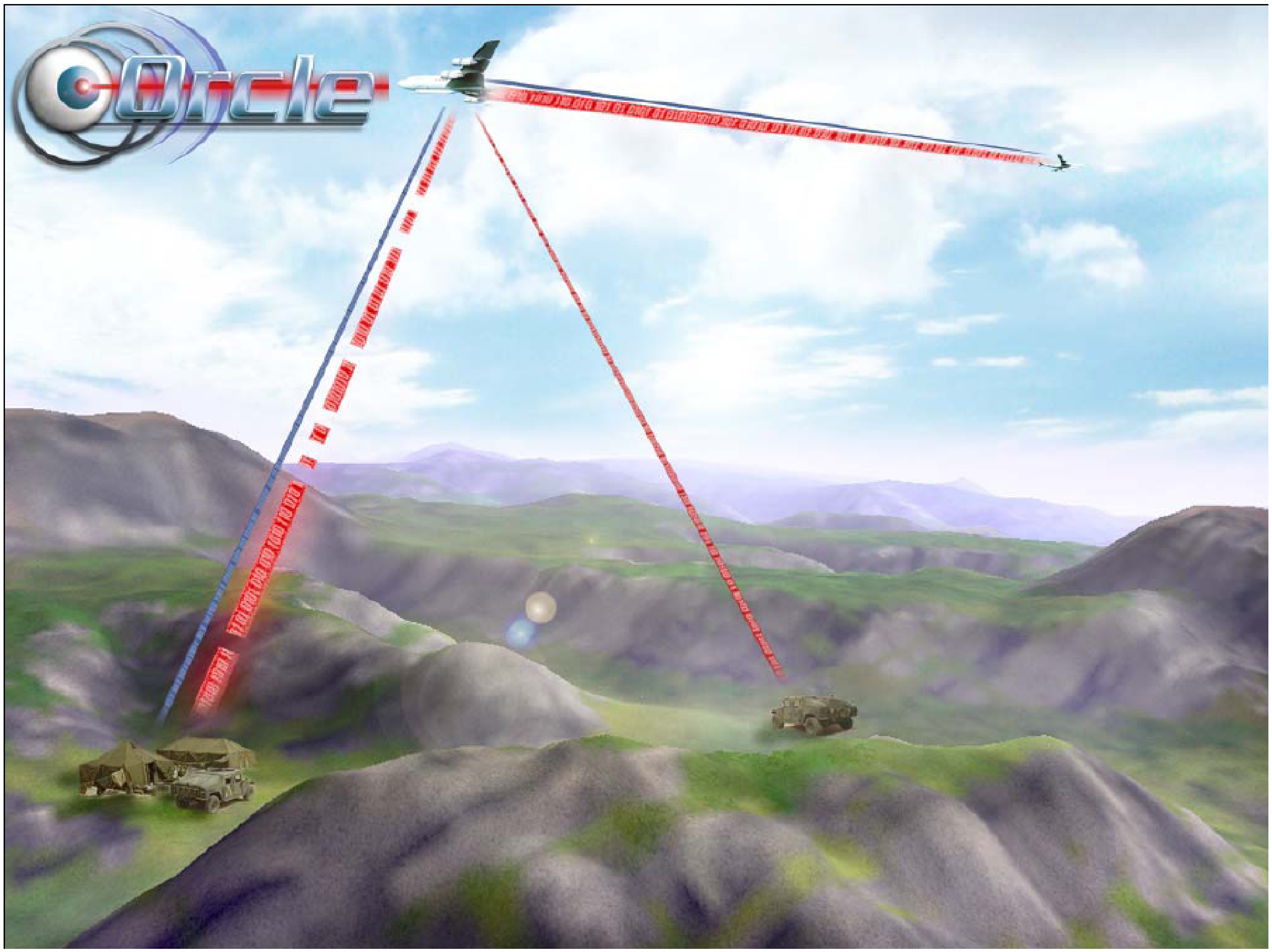
- Room illumination can be harnessed to provide inexpensive, high rate links.

Free-Space Optical Communications



- High-speed (<2 Gbps) fiber extension over 1-4km

Free-Space Optical Communications



Free-Space Optical Communications

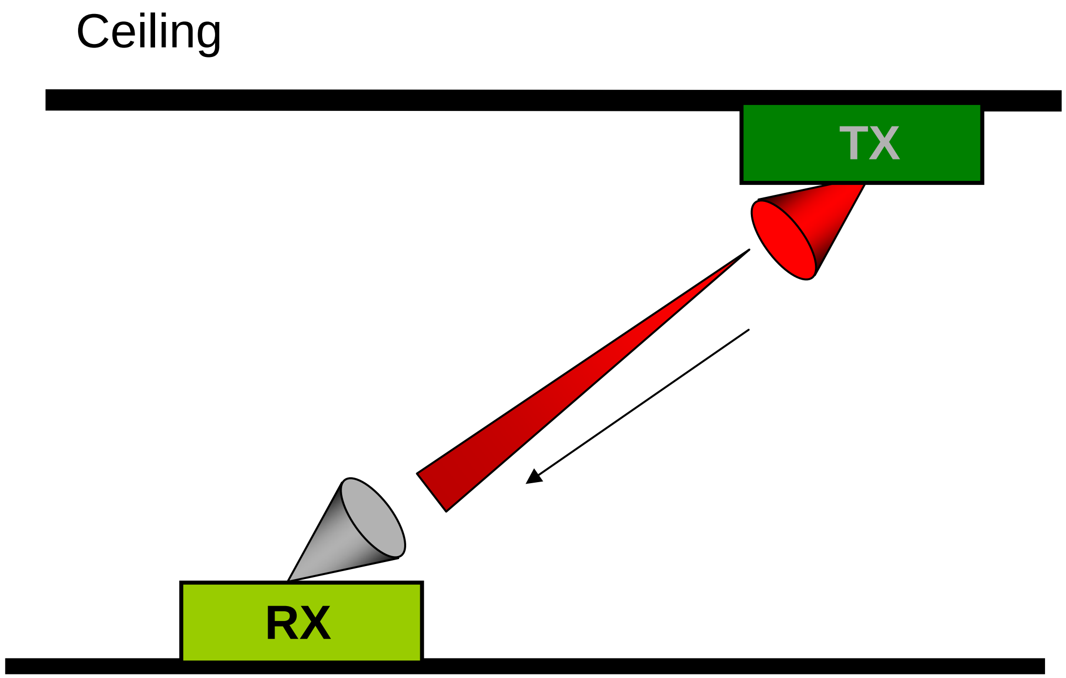
- ESA Artemis experiment
- LEO to GEO communication (link range approx 45,000 km!)

Indoor Optical Wireless Links

- Indoor OW links are an attractive compliment to existing RF links

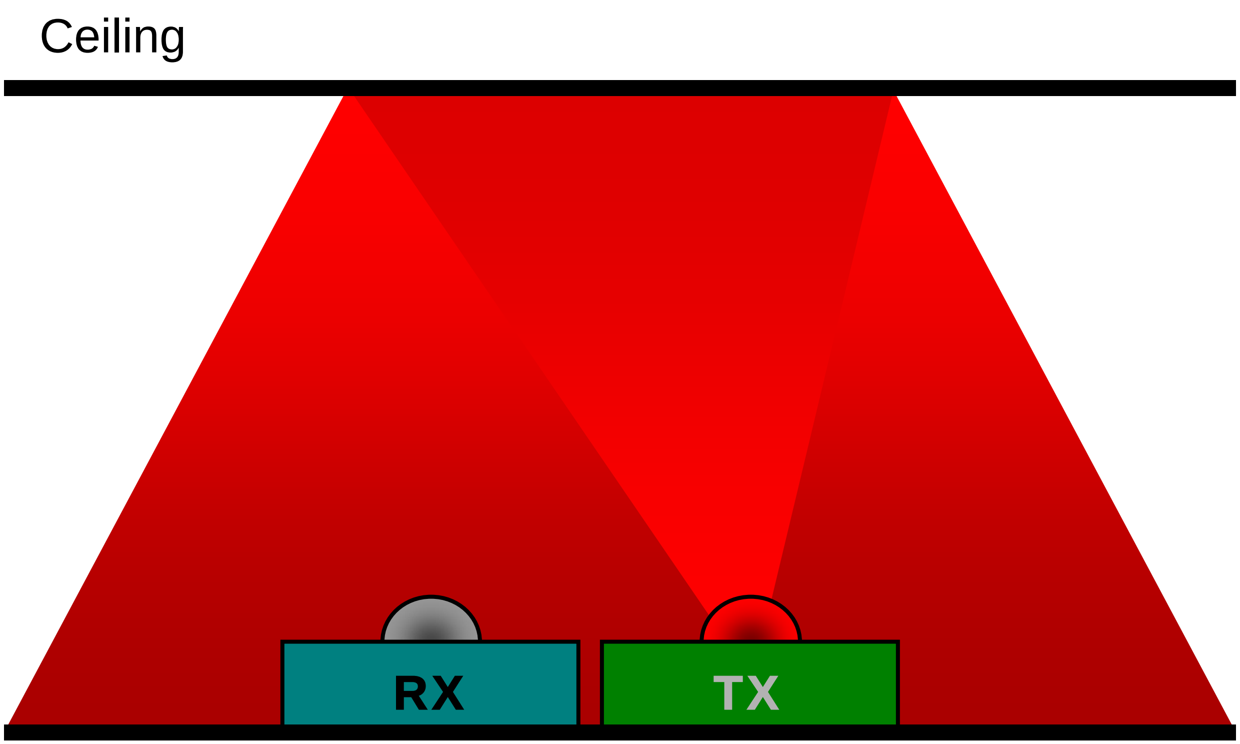
- Must take into account **amplitude constraints**!
  - Amplitude non-negativity constraint
  - Average amplitude constraint

Line-of-Sight Architecture



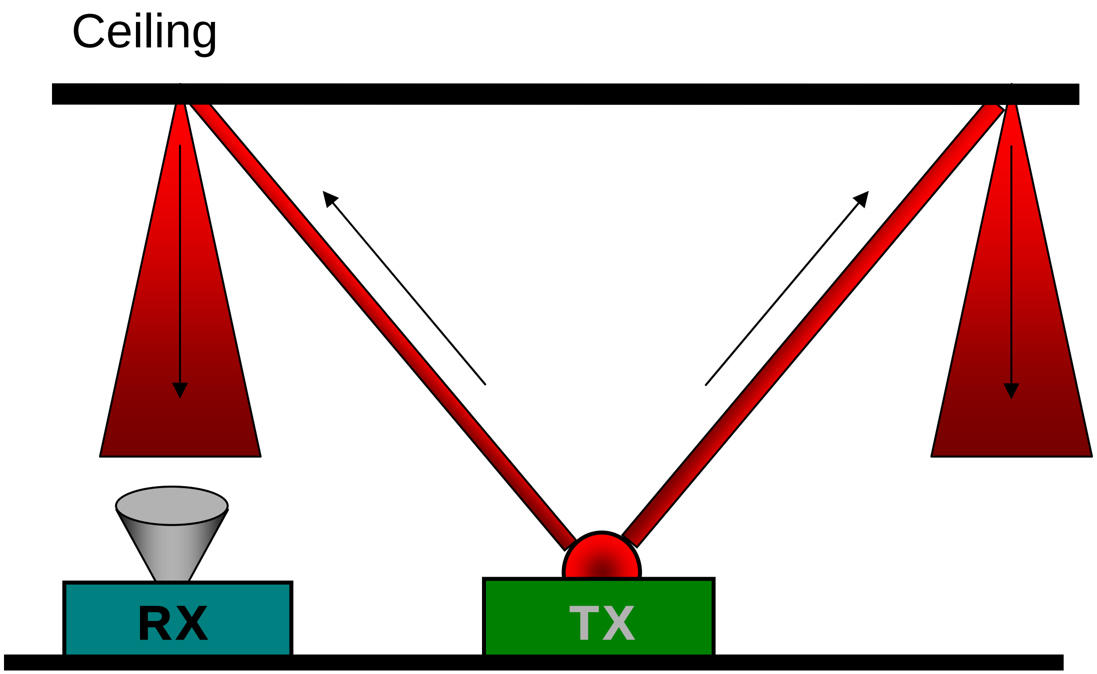
- High bandwidth
- High received SNR
- Low user mobility (w/o tracking)

Diffuse Indoor OW Architecture



- High user mobility at a cost of low received optical power and multipath distortion
- No *fading* for indoor OW communications

Multi-Spot Diffusing Architecture

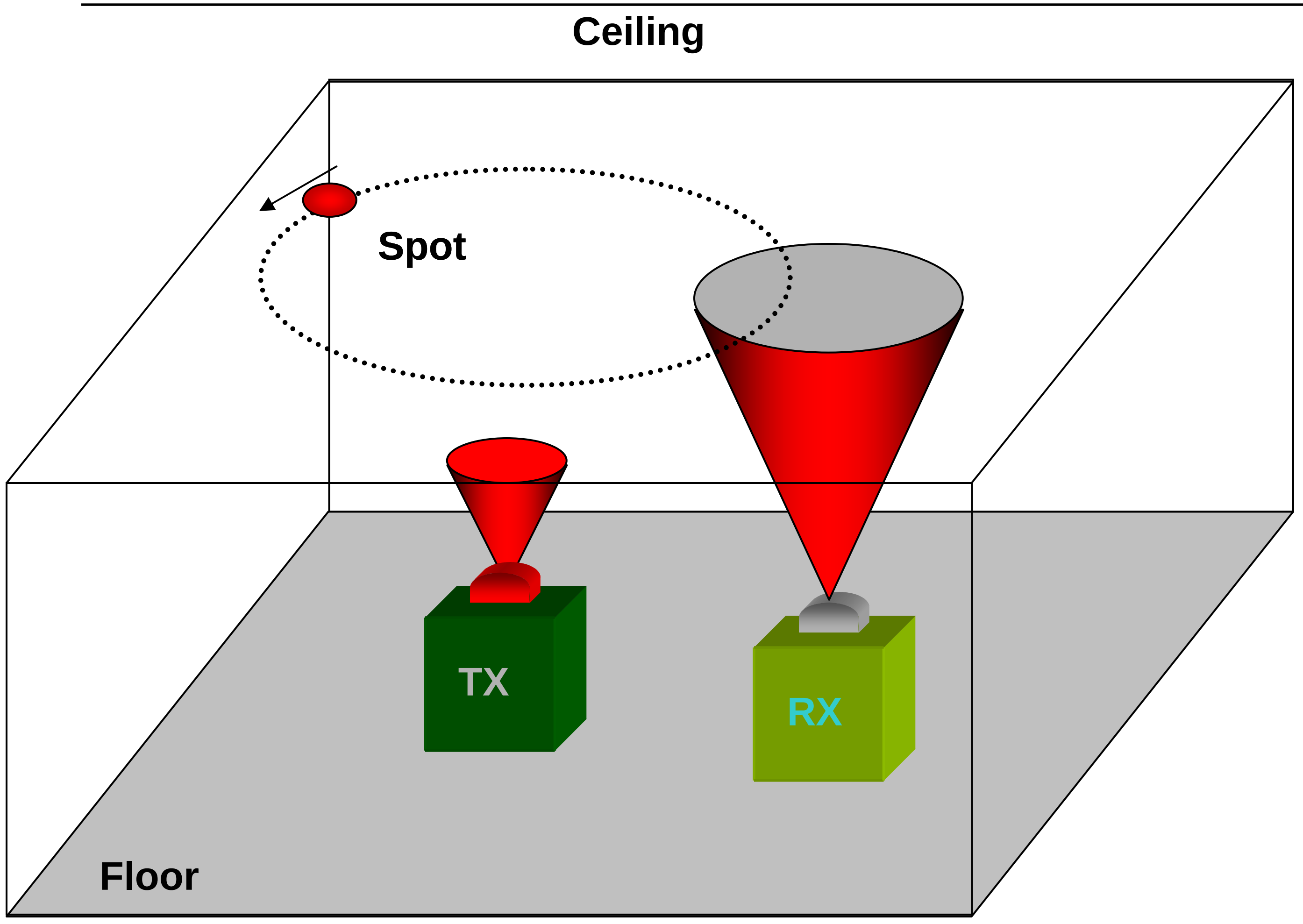


- Higher receiver SNR
- Low multipath due to quasi-LOS path
- Complex transmitter must be designed for each room

Indoor OW Topologies

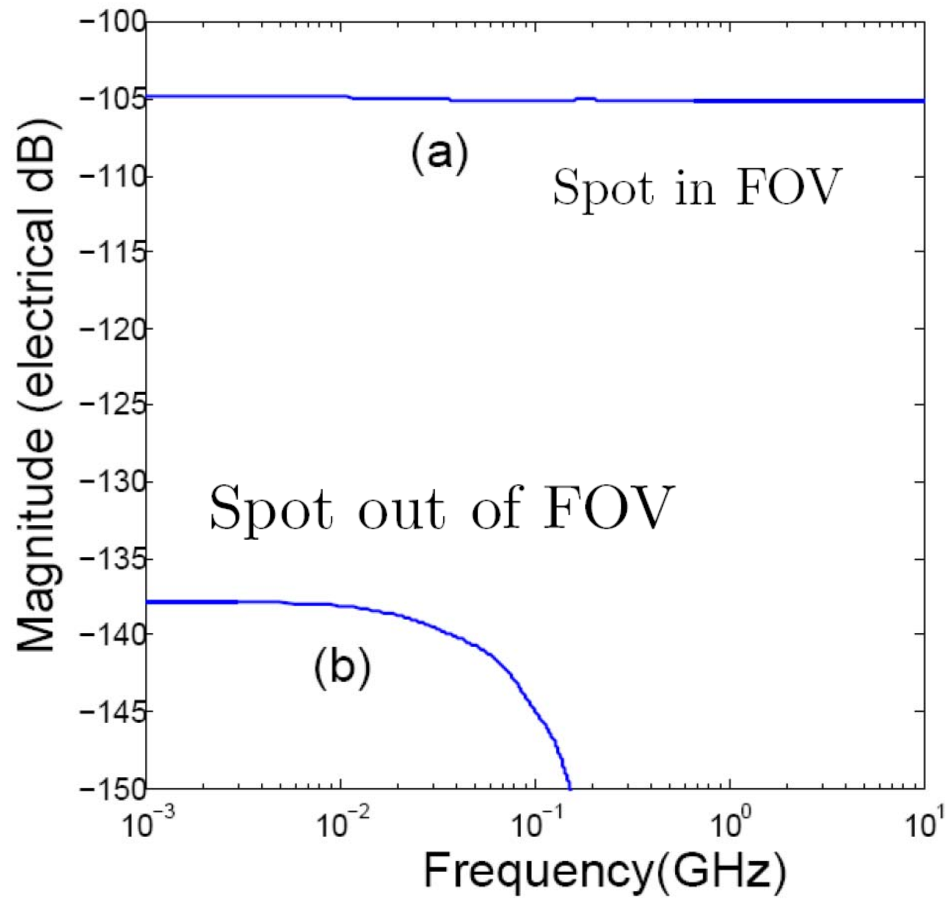
- Point-to-point links have high bandwidth and SNR
  - Require pointing
- Diffuse links permit mobility
  - At expense of bandwidth and SNR
- Multispot Diffusing links permit mobility and good SNR
  - Complex transmitter which cannot be easily modified for different rooms.

Dynamic Spot Diffusing Channel

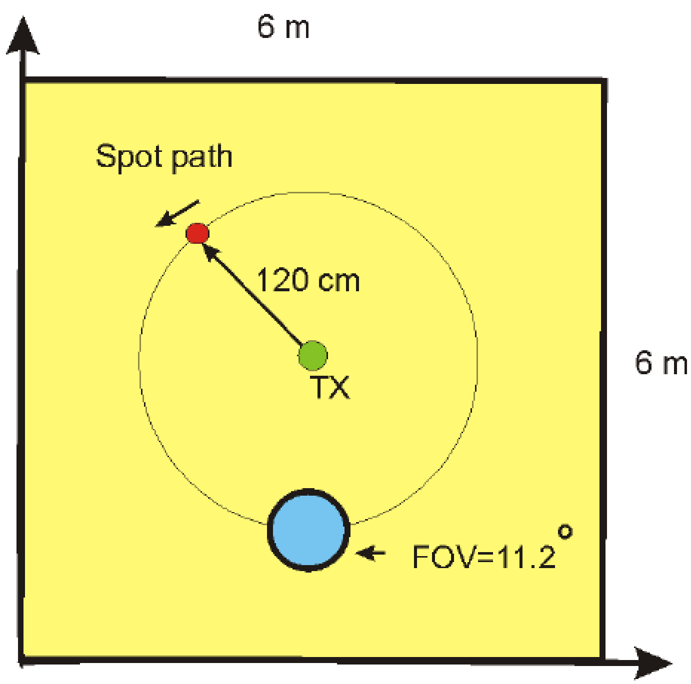


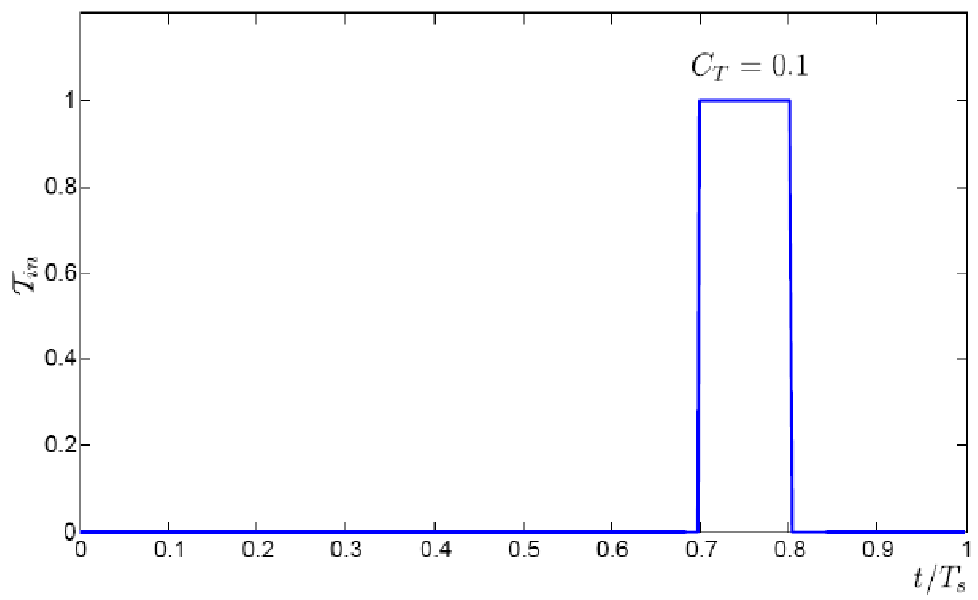
DSD Channel Model

- Two States:
  - High SNR
  - Low SNR
- Flat in band of interest



DSD Channel Capacity



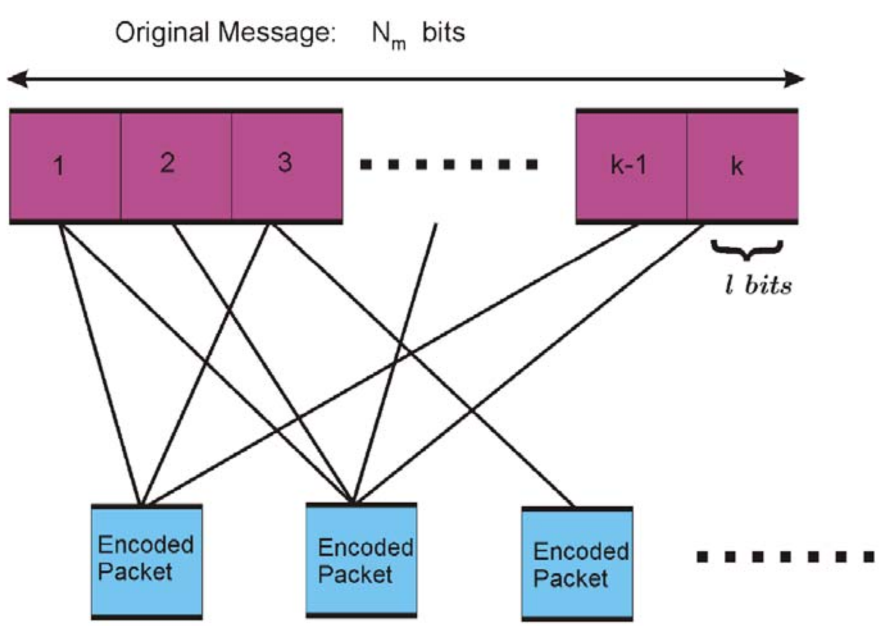


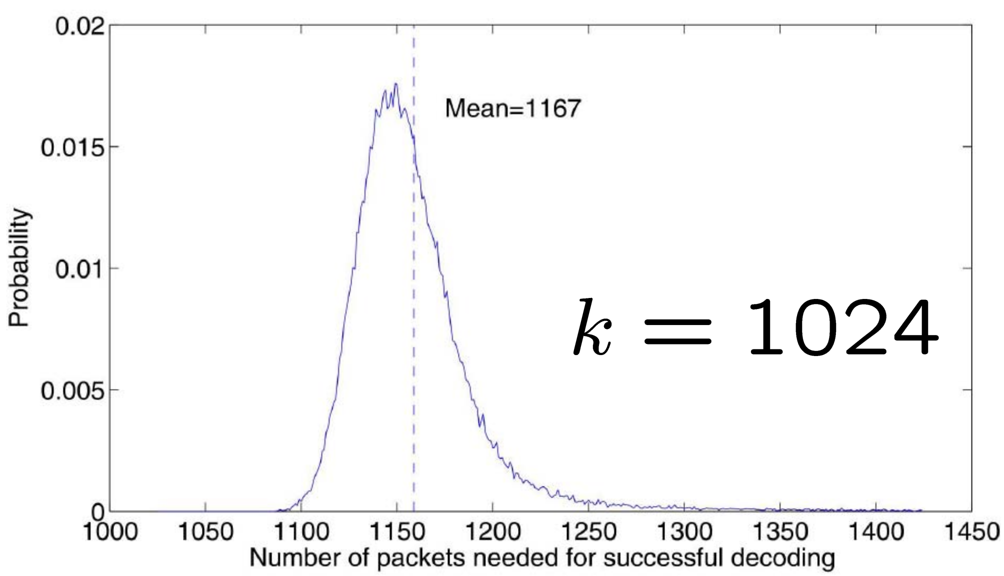
Channel Coding

- DSD channel well modelled as an erasure channel
  - Fixed rates codes are not appropriate
- Rateless Codes (Fountain Codes)
  - Do not require knowledge of erasure probability

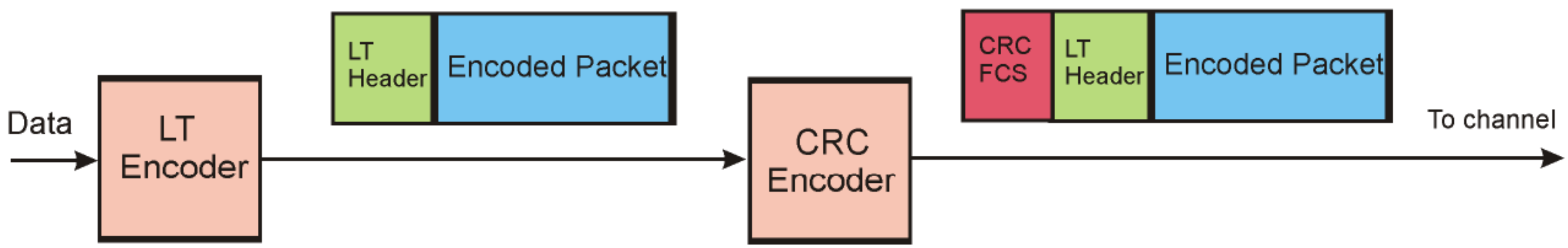
Channel Coding

- Rate of these LT codes adapts to the position in the room
- The number of received packets required for successful decoding is random



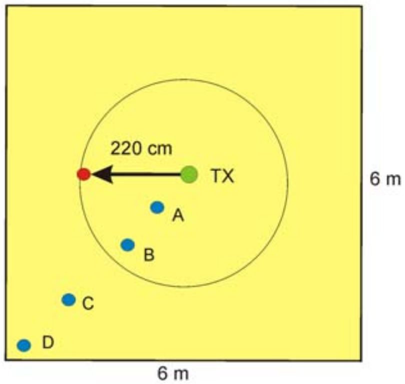


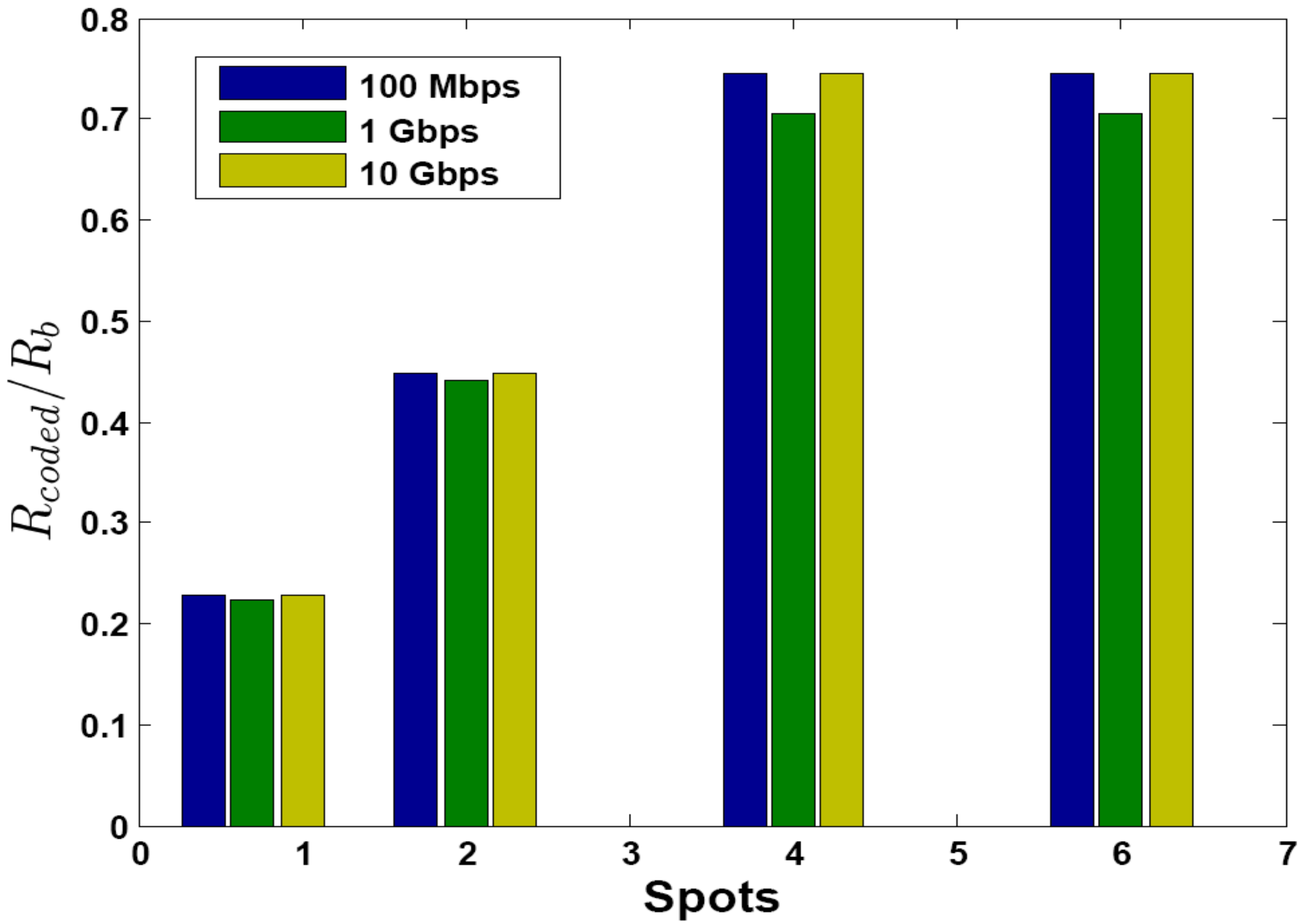
DSD Coding Module



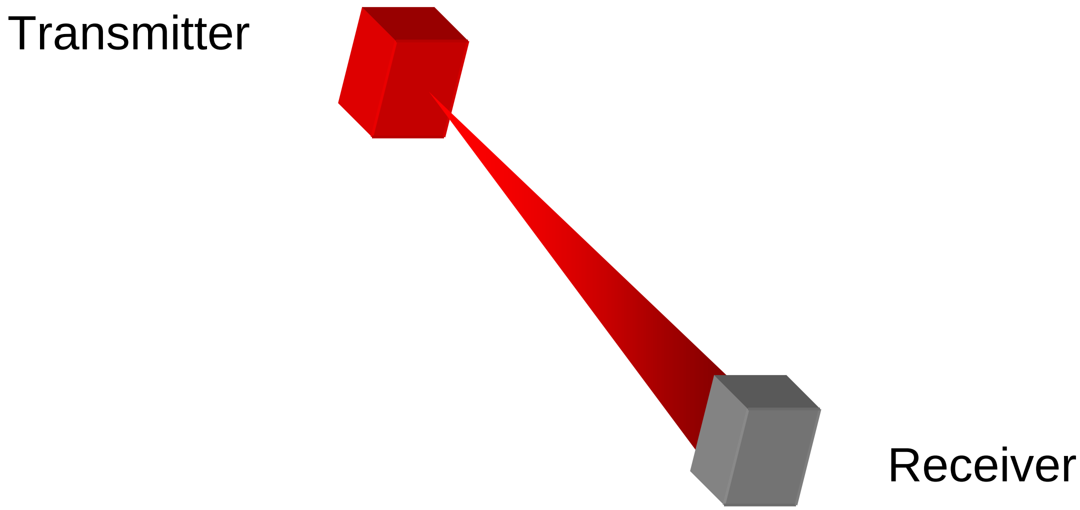
Normalized Rates for Position B

- 100 Mbps TX, OOK, SNR=15.5 dB
- 1 Gbps TX, 16-PPM, SNR=12.5 dB
- 10 Gbps TX, OOK, SNR=13.5 dB





Single Element Systems

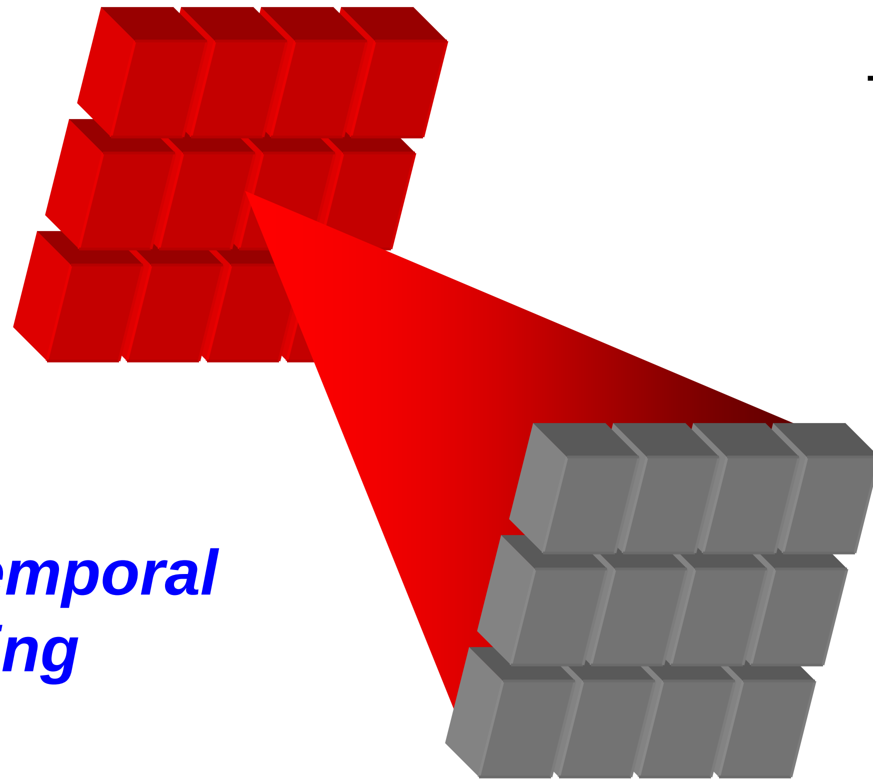


- Spectral efficiency improved by careful pulse selection

Multi-Pixel Optical Link

Transmitters

On order of
1000x1000



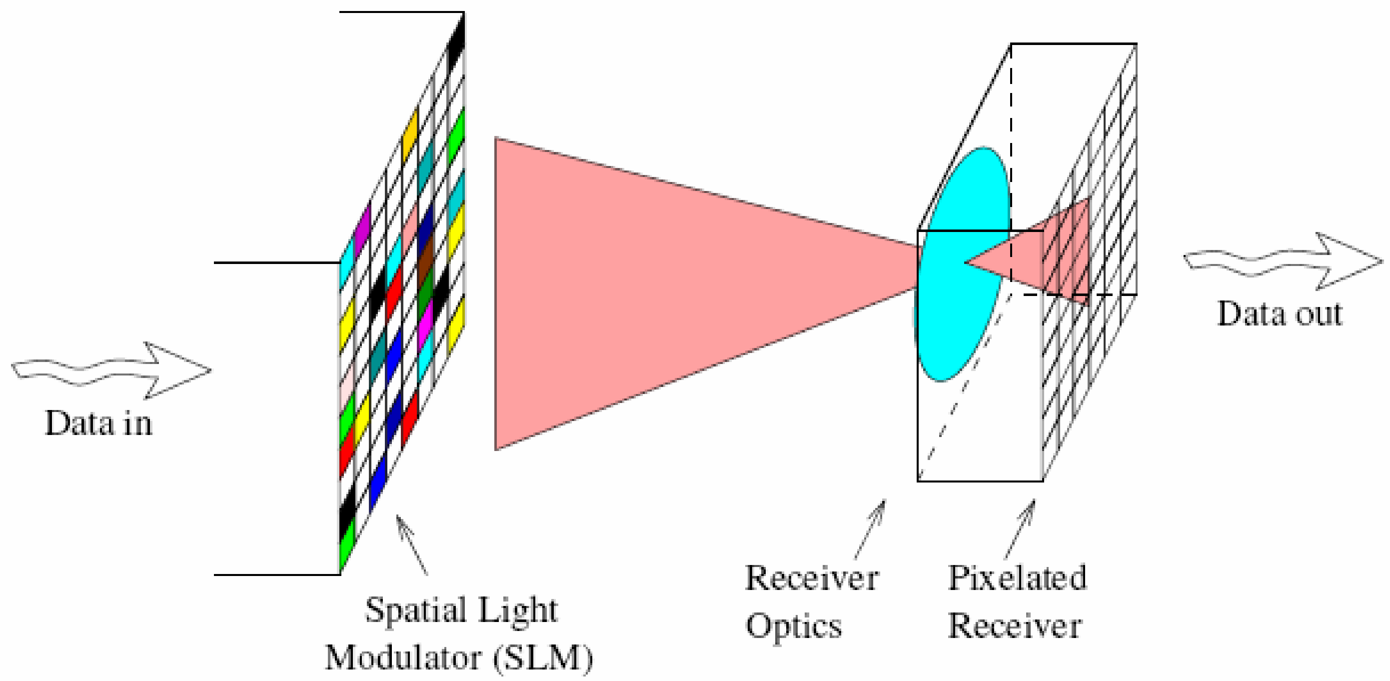
Transmit a
series of
images !

Spatio-temporal
coding

Receivers

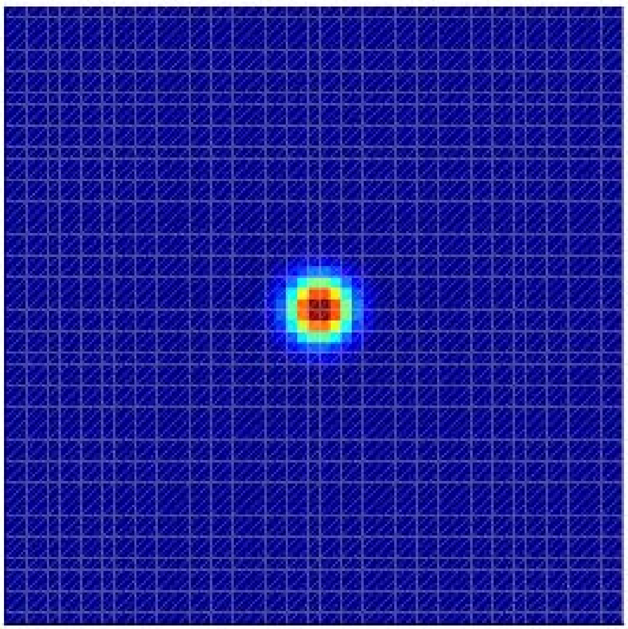
On order of
1000x1000

MIMO Wireless Optical Channel

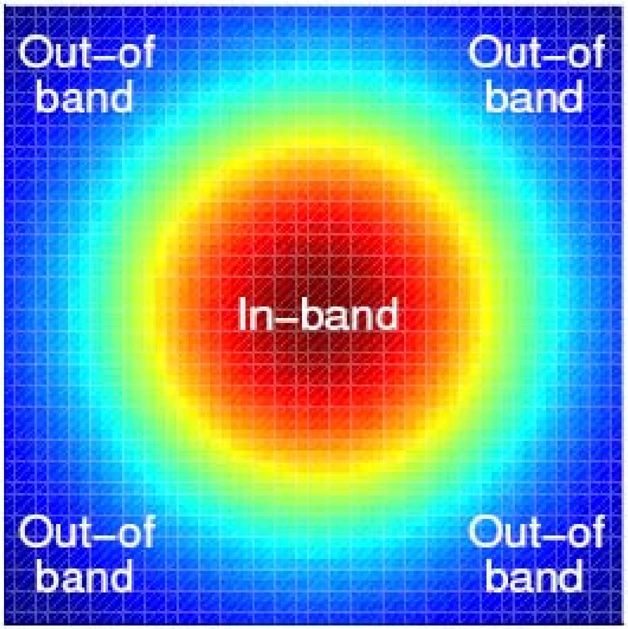


- Pixel shapes and optics modelled by a lowpass point-spread function $h(x,y)$
- High resolution SLM's exist

MIMO Wireless Optical Channel



Point Spread Function
(Spatial Intensity Domain)

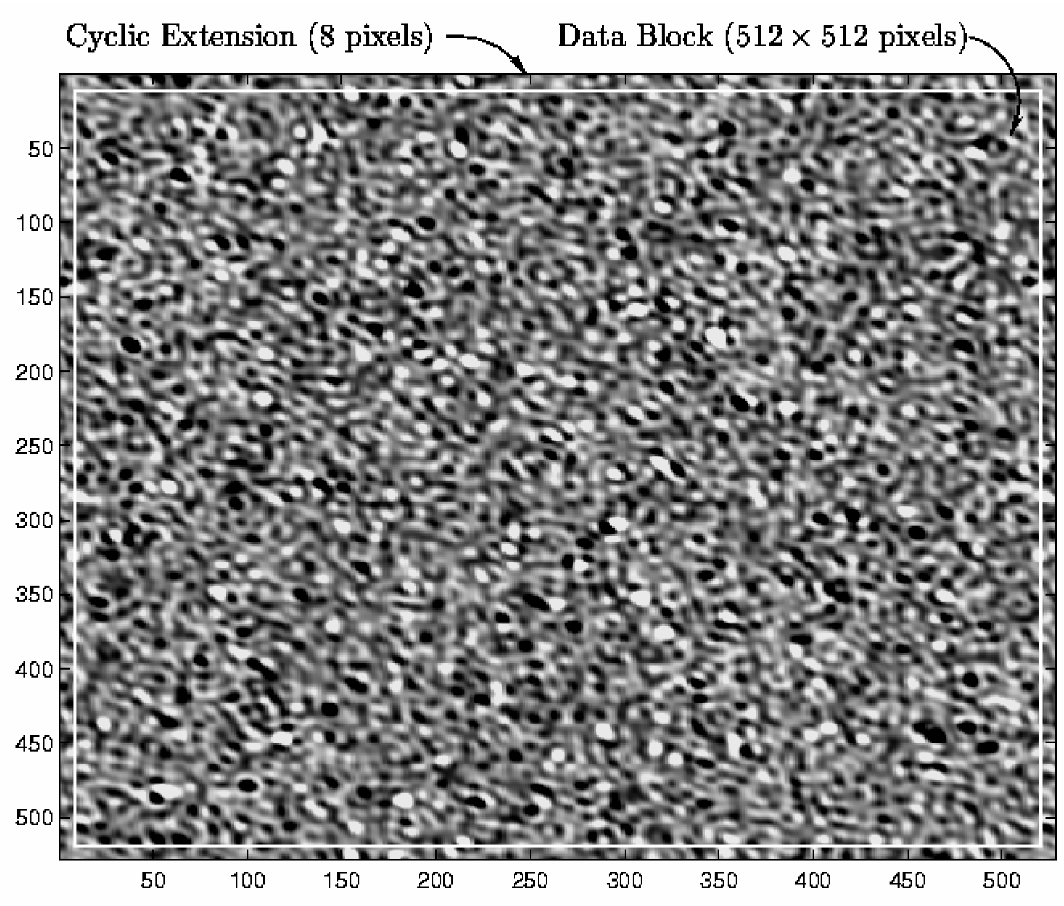


Optical Transfer Function
(Spatial Frequency Domain)

Pixelated Wireless Optical Channel

- **Spatial Discrete Multitone Modulation** (SDMT)
  - Data loaded in low spatial frequency
  - Append cyclic extension around image
  - Water pouring over spatial frequency bins

SDMT Symbol

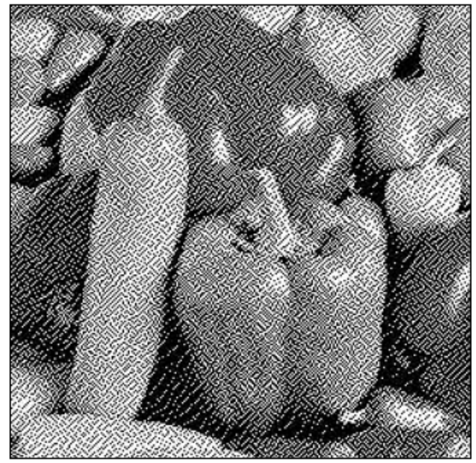

Cyclic Extension (8 pixels)
Data Block (512 × 512 pixels)
50
100
150
200
250
300
350
400
450
500
50
100
150
200
250
300
350
400
450
500

Out-of-Band Techniques

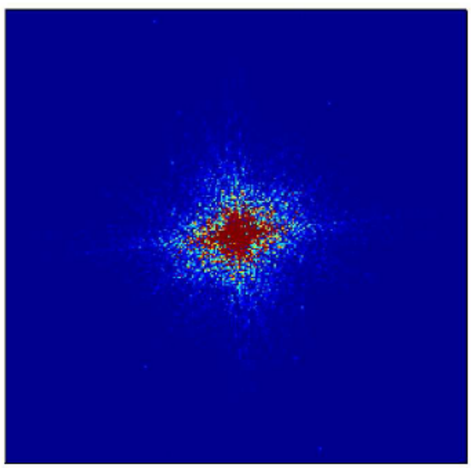
- **Problems**:
  - Non-negativity constraint
  - Need high-dynamic range SLM
- **Proposed Solution**:
  - High-speed binary-level SLMs exist!
  - Use the degrees of freedom in the out-of-band spectrum to satisfy amplitude constraints
  - Δ-Σ modulation in space
    - Shape quantization noise out-of-band

Error Diffusion Halftoning

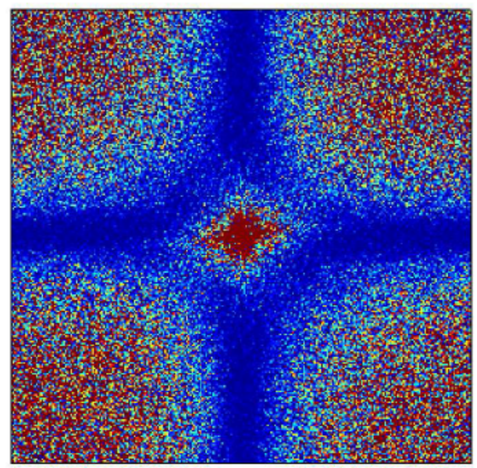
Analog Image



Binary Image

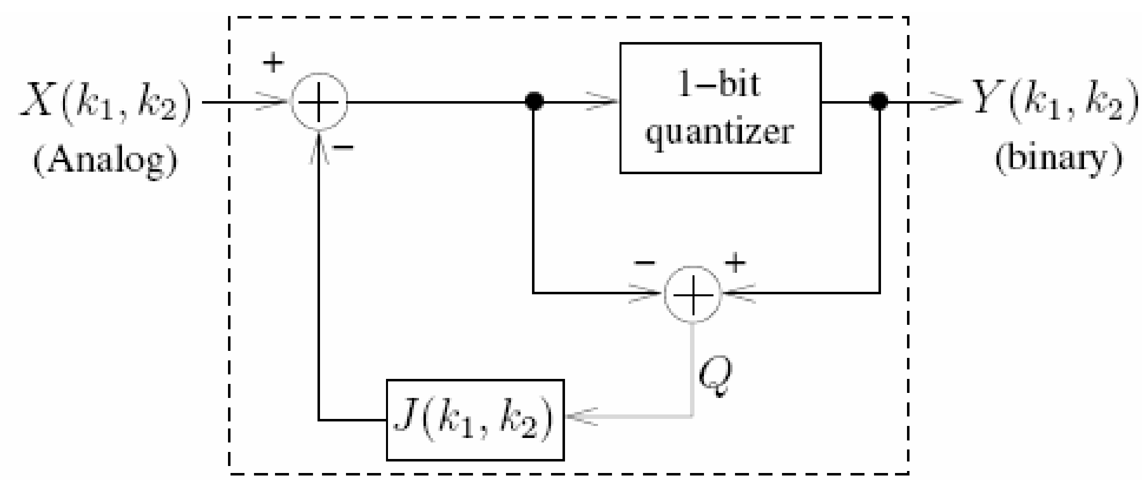


PSD of Analog Image



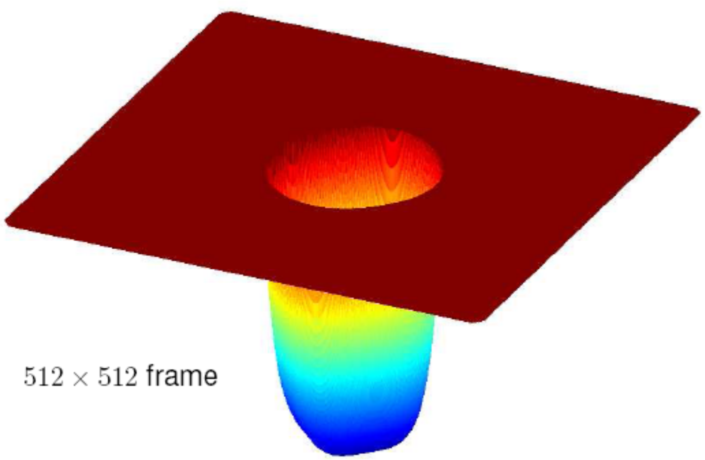
PSD of Binary Image

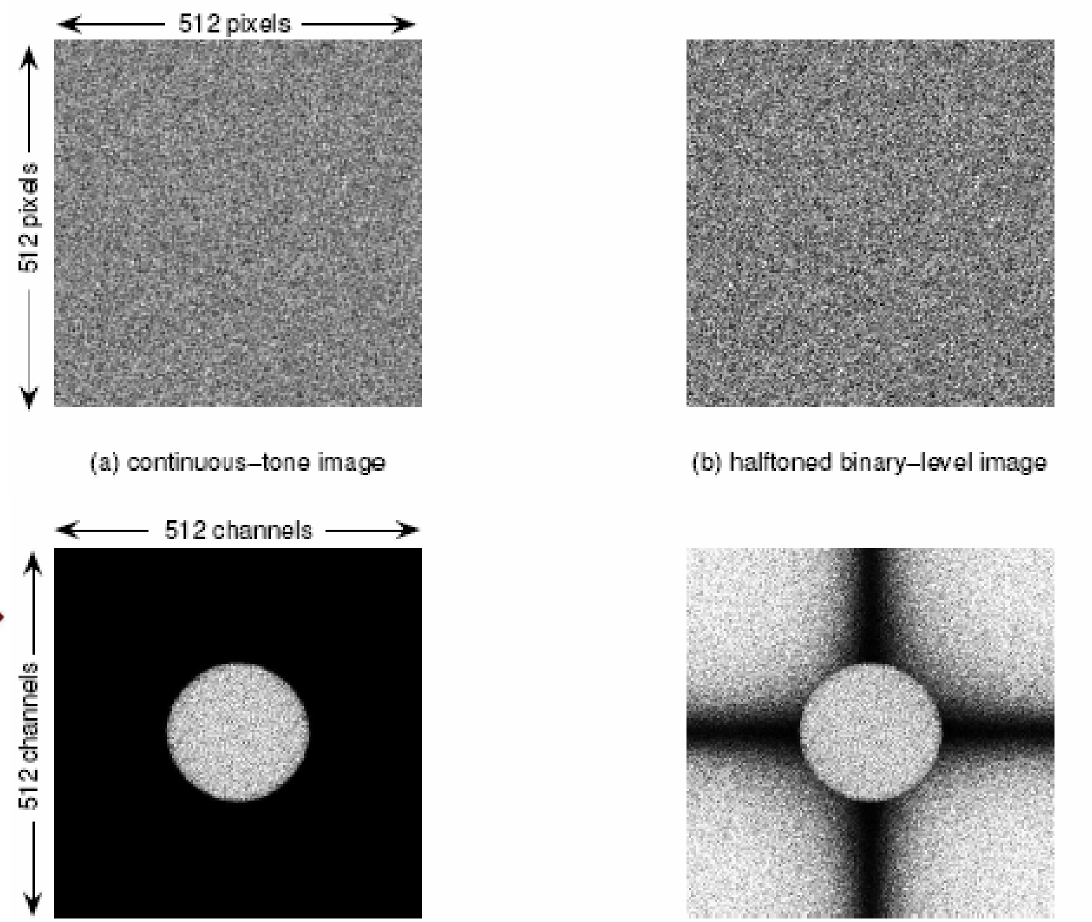
Halftoned Spatial Discrete Multitone



- **Image Processing**:
  - Feedback filter $J(k_1,k_2)$ shapes quantization noise to high frequencies out of perceptual range
- **Optical Communication**:
  - Feedback filter $J(k_1,k_2)$ shapes quantization noise to high frequencies which are attenuated by channel
    - Choose $J()$ to maximize the ***channel capacity***

Optical Power Limited System





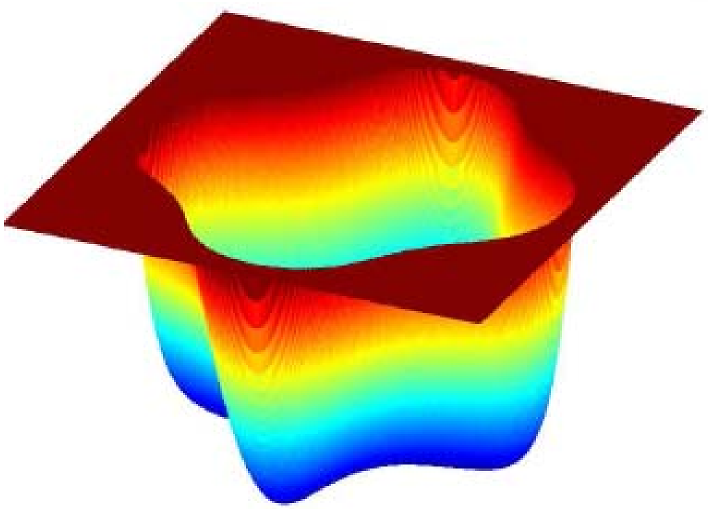
(a) continuous–tone image

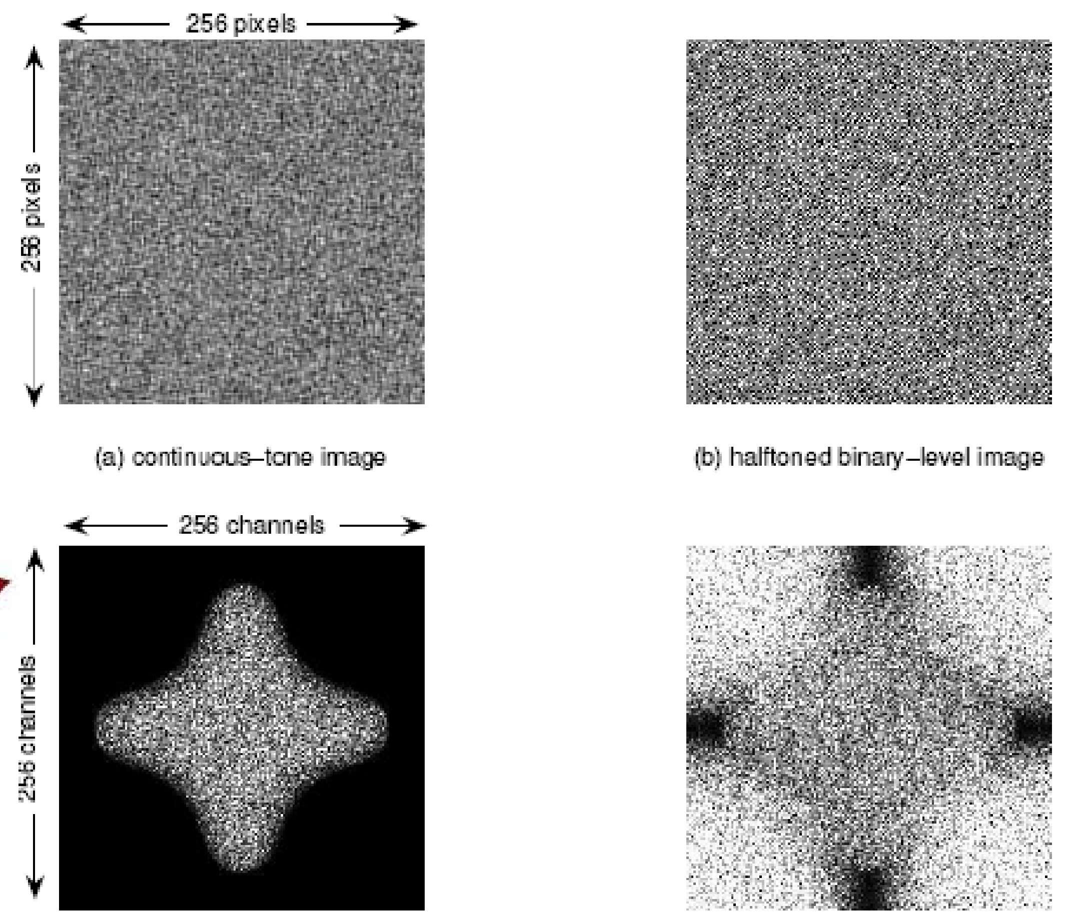
(b) halftoned binary–level image

(c) continuous–tone image spectrum

(d) halftoned binary–level image spectrum

Quantization Noise Limited System





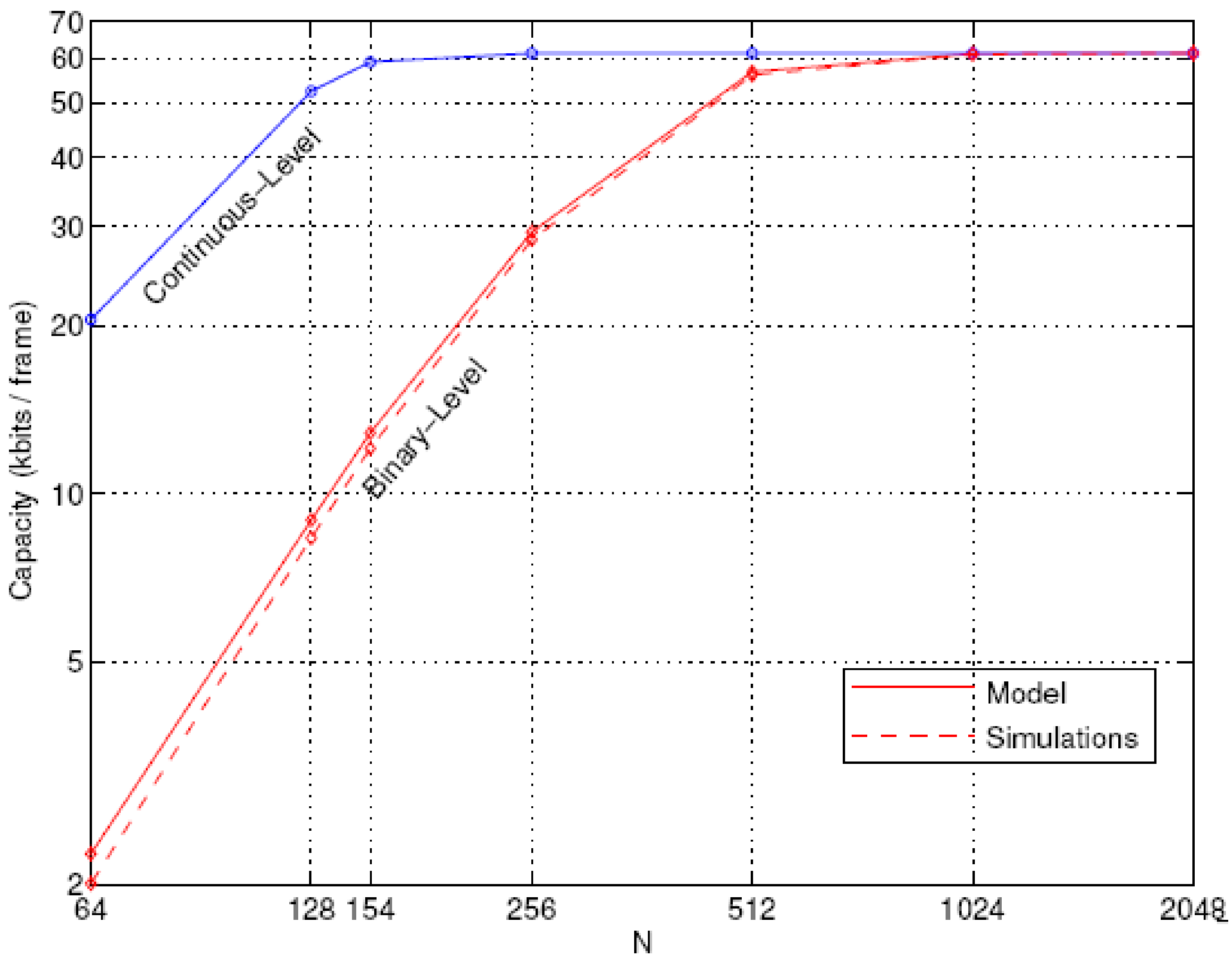
(a) continuous–tone image

(b) halftoned binary–level image

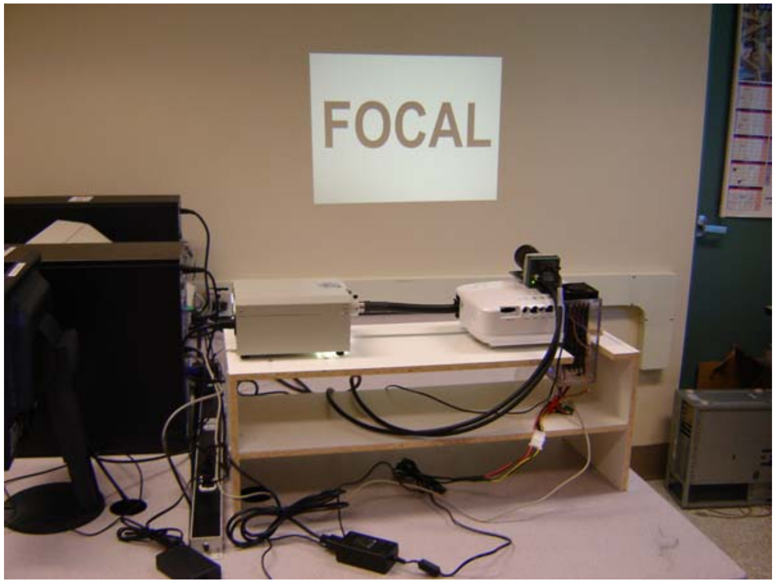
(c) continuous–tone image spectrum

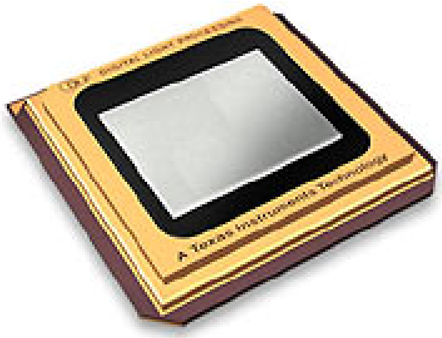
(d) halftoned binary–level image spectrum

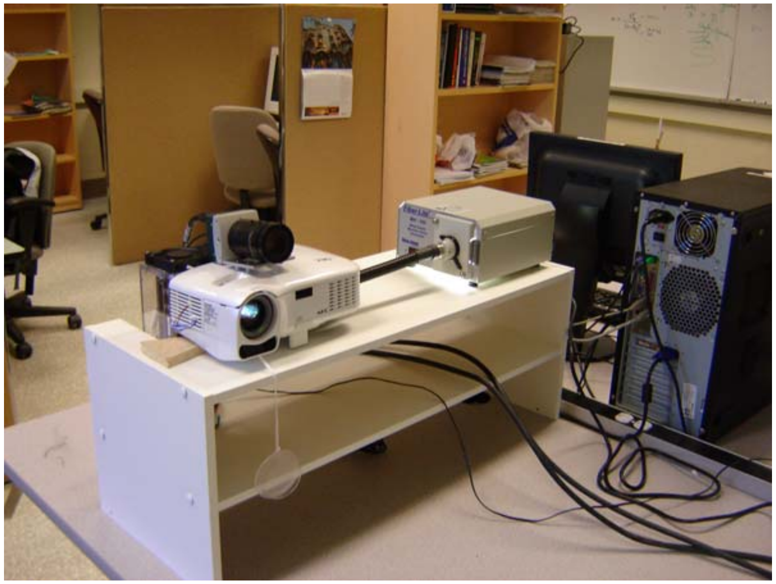
Capacity Results



Prototype MIMO Wireless Optical Link







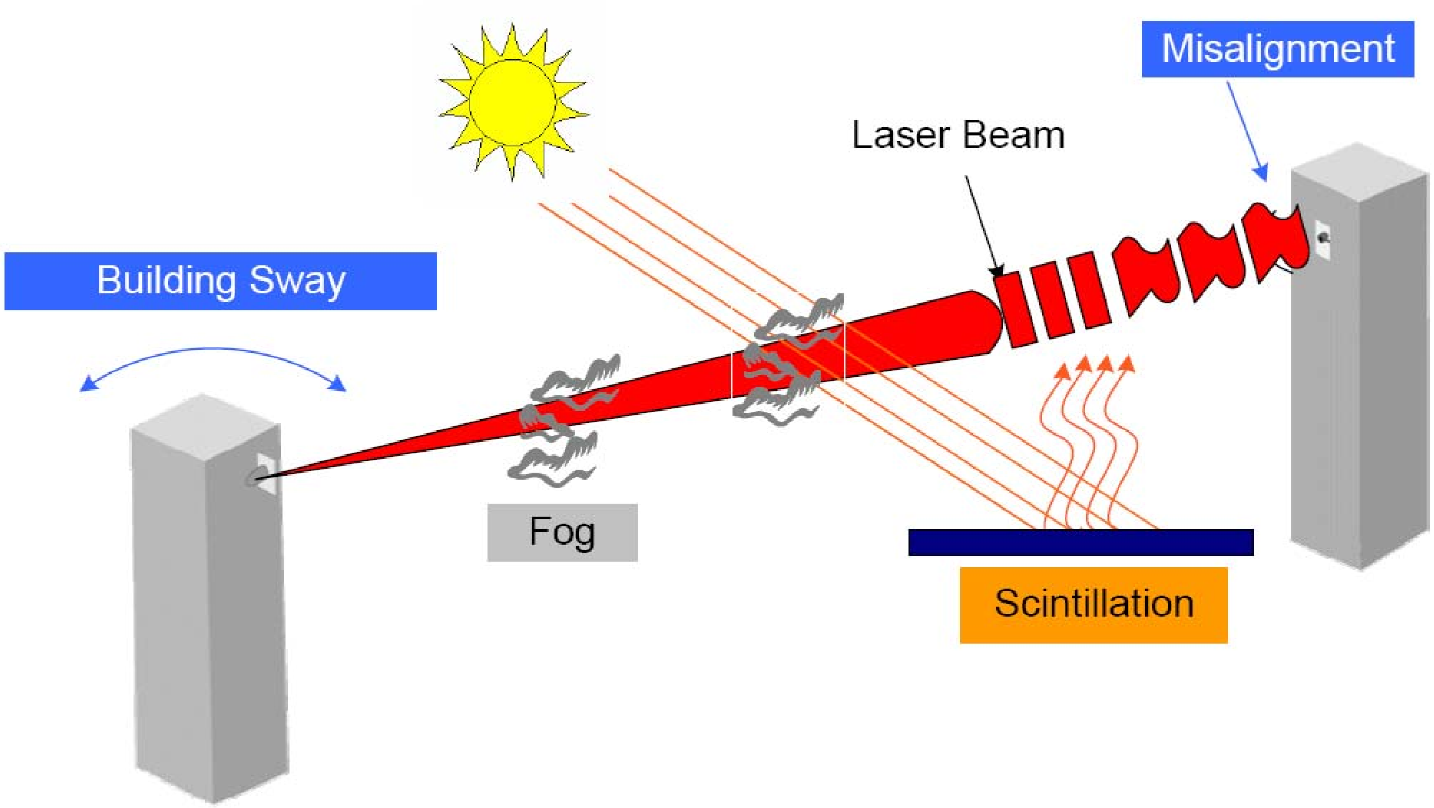
Free-Space Optical Links

- There is a great need for high-speed (Gbps) wireless access medium
  - It is estimated that **75%** of commercial buildings in the US are within **1 km** of a major fiber trunk, but only **5%** of these are connected to that trunk.
- FSO Links provide a virtual extension of backbone fiber network at a comparatively low cost!

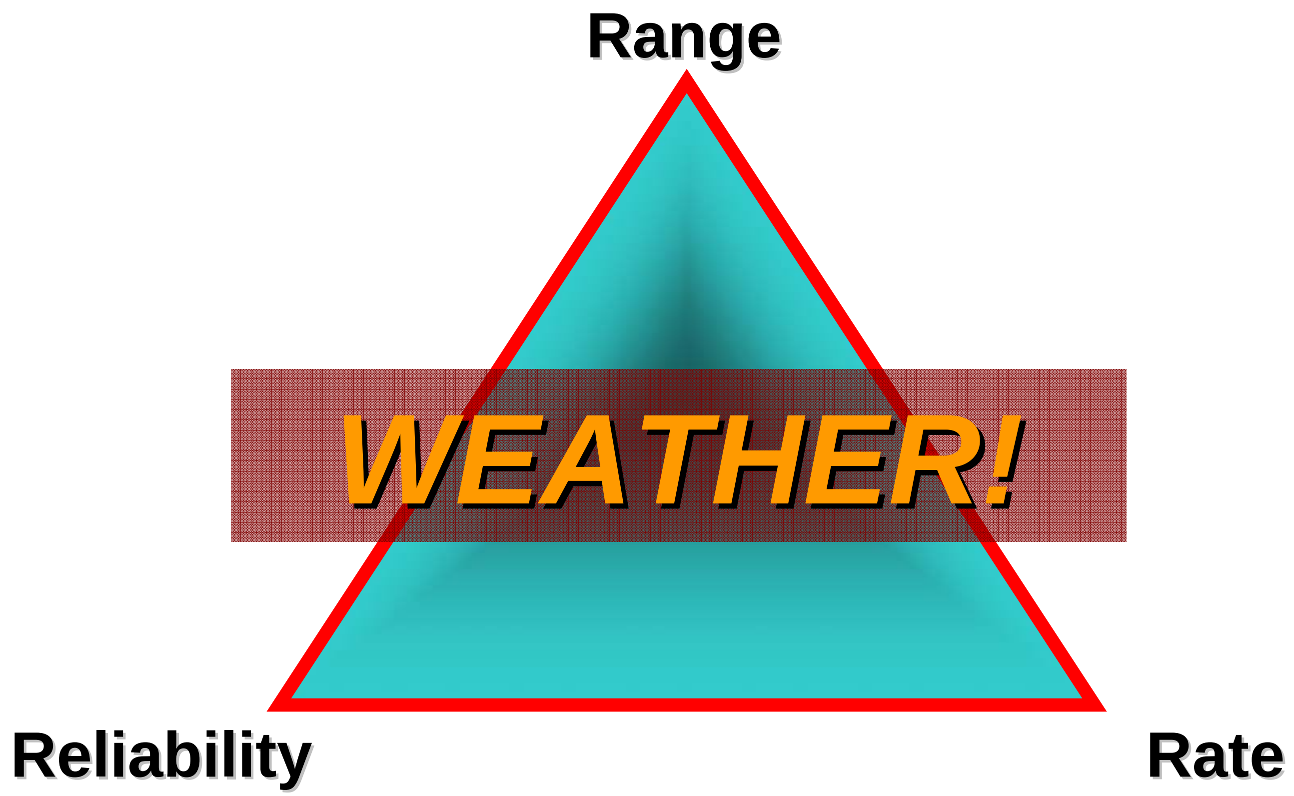
Advantages of FSO

- High data rate, LOS point-to-point links
- Inexpensive (as compared to fibre)
- Rapidly deployed and reconfigurable
- Immune to RF interference
  - Can be used in areas with RF congestion, i.e., MAI limited
- Secure

FSO Link Impairments



The 3 R's of FSO



Weather

6.5 dB/km 150 dB/km 225 dB/km

300 m distance to tall building; line is 2.4 km

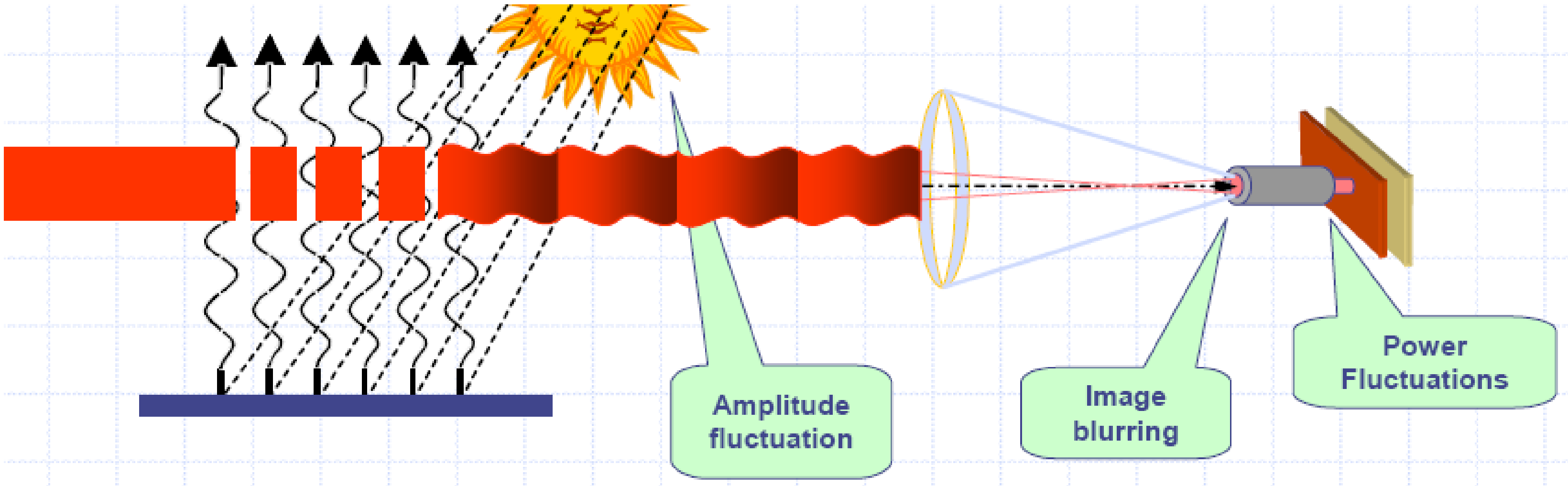
Denver Colorado, Fog events

FSO Range and Rates

- Commercial systems operate at ranges of 1-4 km at rates < 2 Gbps
- Single and Multiple beam systems
- Active tracking is employed in more expensive systems to mitigate pointing errors
  - Inexpensive systems use a wide beam width at cost of lower SNR (i.e. range)

FSO Fading

- Amplitude fluctuation due to variation of refractive index of air along propagation path
- Slow fading
  - Coherence time on order of 10 ms while bit period is on order of 1 ns!
- Increases drastically with range



FSO Reliability

- FSO customers roughly divided according to reliability requirements

- **Carrier-Class** Customers
  - Service providers such as Bell and Rogers
  - Availability requirements of 99.999% (5 nines)
- **Enterprise** Customers
  - University campuses, hospitals, companies
  - Availability requirements 99%

FSO Link Outage Capacity Based Design

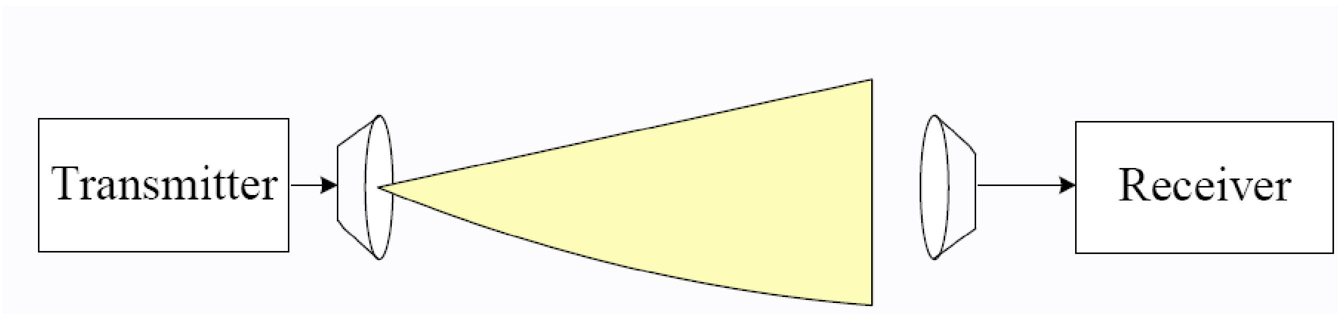
- Question:
  - For a given **range**, how to select beam width to maximize **rate** for a given **reliability**?

- Reliability is quantified by probability of **outage event**

$$P_{\text{out}} = \text{Prob}(\mathcal{C}(h) < R_0)$$

FSO Link Outage Capacity Based Design

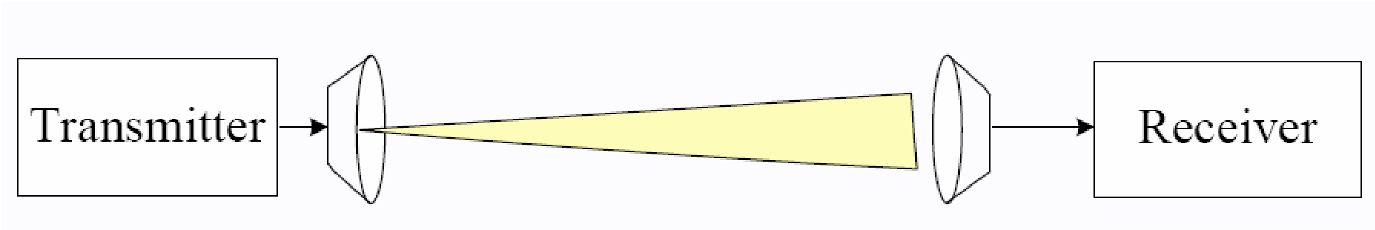
- **Answer**: (partial)
  - Wide Beam: mitigates pointing error at expense of low SNR at receiver



$$y = \underbrace{h}_{\mathbf{h_a} h_{\mathrm{p}}} x + n$$

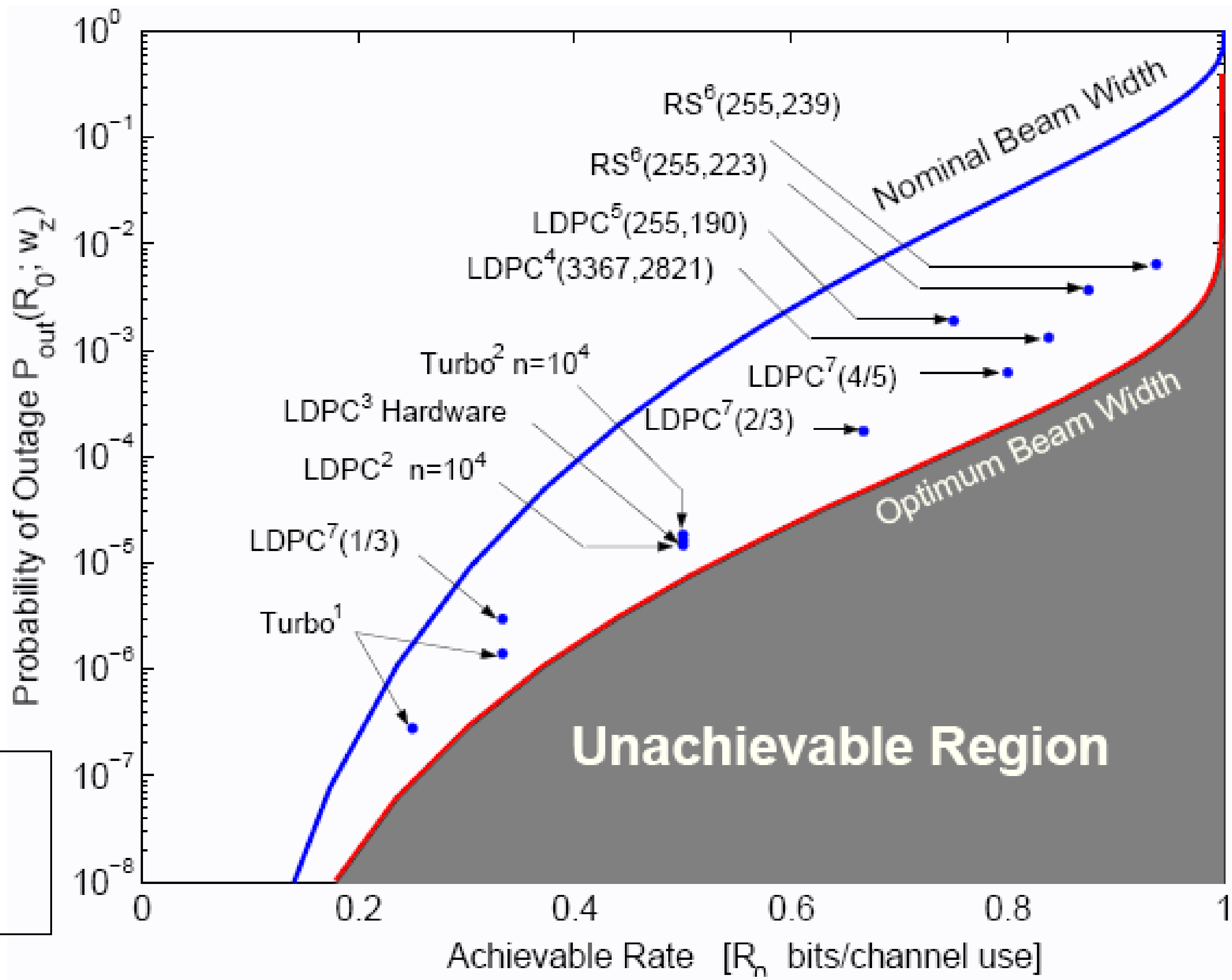
FSO Link Outage Capacity Based Design

- Answer: (partial)
  - Narrow Beam: More severe pointing error, higher instantaneous SNR at receiver



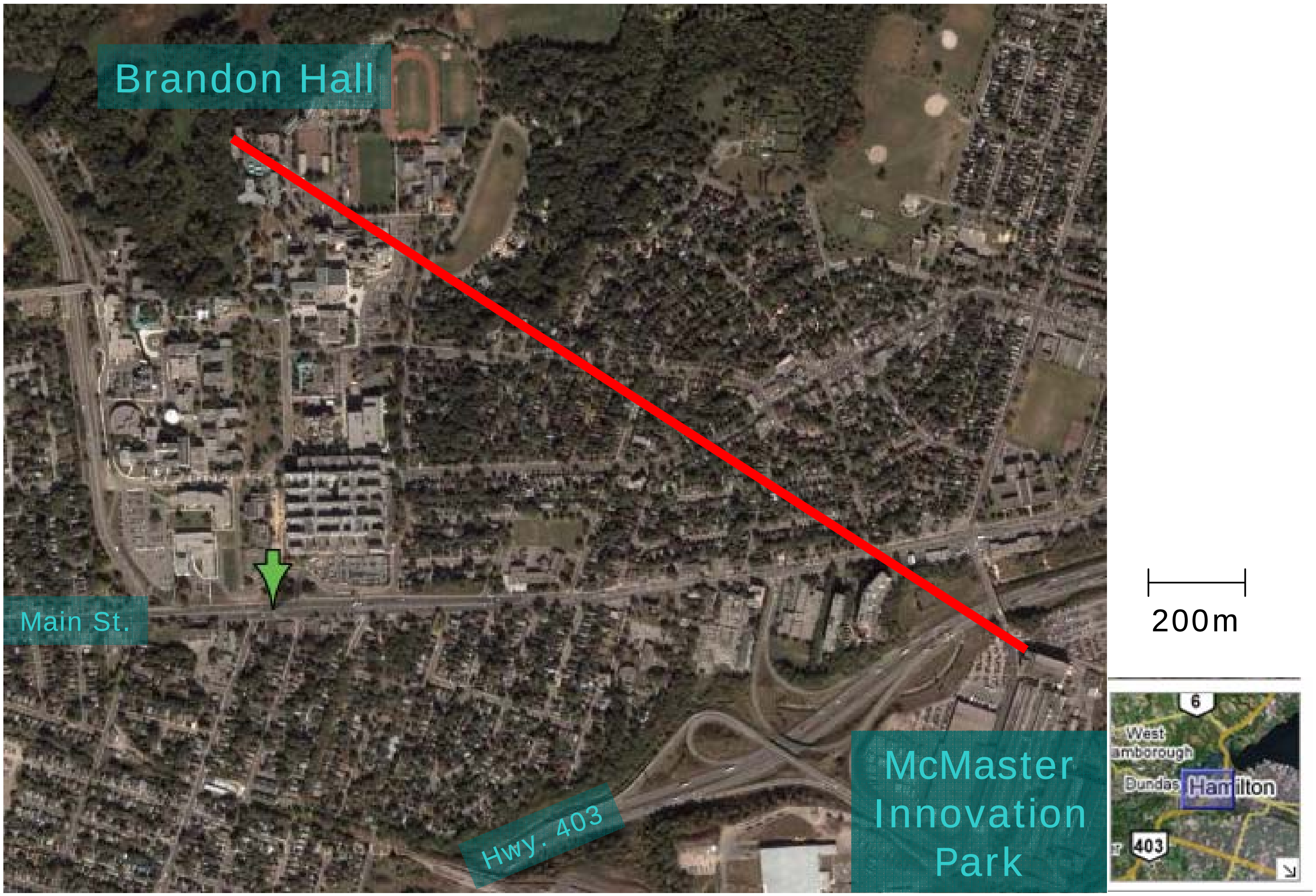
$$y = \underbrace{h}_{h_{\mathrm{a}}\mathbf{h}_{\mathbf{p}}} x + n$$

Achievable Pairs (P_{out}, R_0)



Light fog, log-normal fading (σ_R^2=0.1), P=16dBm

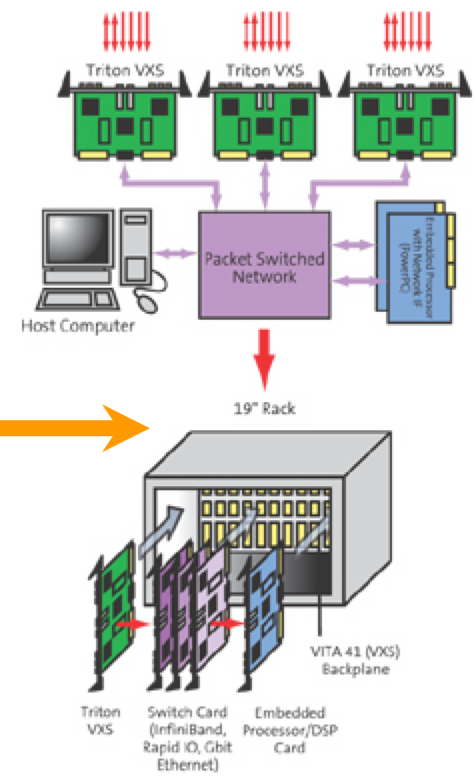
FSO Testbed at McMaster University



Google Maps, 2007

FSO Testbed at McMaster University

Courtesy fSona Inc.



Conclusions

- Optical wireless is a viable compliment to RF communications
  - Large rates are available due to vast amounts of unregulated bandwidth
  - Immune to RF interference and cross-talk
  - Rapidly deployable and reconfigurable Gbps links

Current and Future Directions

- Hybrid RF-FSO links
  - To improve reliability of link
  - For mitigation of interference limited networks (frequency planning)
  - For use in backhaul of WiMAX and like networks
- MIMO FSO communications
- Indoor Optical Impulse Modulated Wireless Systems

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